

1044b UIC - EAST POPLAR OIL FIELD
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occurred because of differential subsidence rates and an overall relative rise in sea level. The coupling of eolian sequences with their controls allows not only an understanding of the resultant facies architecture, but also shows the response of continental systems on basin margins to basin interior events.

Nº 4371

HYDROGEOLOGIC ASPECTS OF BRINE DISPOSAL IN THE EAST POPLAR OIL FIELD, FORT PECK INDIAN RESERVATION, NORTHEASTERN MONTANA.

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The East Poplar Oil Field encompasses about 70 square miles in the south-central part of the Fort Peck Indian Reservation. Oil production began in 1952 from the Mississippian Madison Group. Production depths range from about 5,500 to 6,000 feet below land surface. Large quantities of brine (water having a dissolved-solids concentration greater than 35,000 milligrams per liter) have been produced with the oil. The brine has a dissolved-solids concentration of as much as 160,000 milligrams per liter.

Most of the brine has been disposed of by injection into shallower subsurface formations (mainly the Lower Cretaceous Dakota Sandstone at depths of about 3,300 feet and the Upper Cretaceous Judith River Formation at depths of about 1,000 feet). Smaller quantities of brine have been directed to storage and evaporation pits. Handling, transport, and disposal of the brine have resulted in its movement into and migration through shallow Quaternary alluvial and glacial deposits along the Poplar River valley. Locally, domestic water supplies are obtained from those deposits.

The major point source of shallow ground-water contamination probably is leakage of brine from corroded disposal-well casing and pipelines. Smaller quantities of brine probably have leaked through storage or evaporation pits that may have been incompletely sealed or that have developed ruptures in the sealing material. Using electromagnetic geophysical techniques and auger drilling, three saline-water plumes in alluvial deposits and one plume in glacial deposits have been delineated. Dissolved-solids concentrations are as large as 14,000 milligrams per liter in the plumes but typically are less than 2,000 milligrams per liter elsewhere. Dominant constituents in plume areas are sodium and chloride, whereas those in nonplume areas are sodium and bicarbonate.

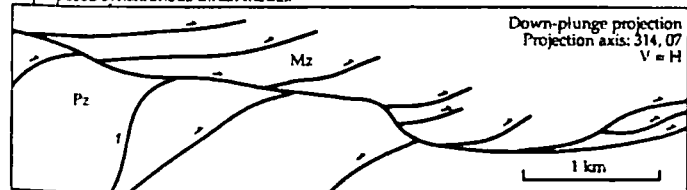
Nº 33864

EVIDENCE FOR SYNCHRONOUS THRUSTING IN THE NORTHERN SAWTOOTH RANGE, MONTANA

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The critical-taper wedge model of thrust belt development requires synchronous and so-called "out-of-sequence" movement on thrust faults to be common. Analysis of new field data reveals a positive test of a recently proposed geometric/kinematic model of synchronous thrusting.

The northern Sawtooth Range in northwestern Montana presents an intriguing pattern on regional maps: thrust faults terminate in the core of a large northwest-trending and -plunging anticline; the anticline folds an overlying detachment and supports on its forelimb a stack of closely spaced and variably folded thrust imbricates. The plunging nature of mapped structures and excellent exposures permit us to observe different structural levels and to incorporate the three-dimensional observations into cross-sections via down-plunge projections. The orientation of down-plunge views and resulting cross-sections is parallel to the mean transport direction. Transport direction was determined using kinematic analysis of mesoscopic asymmetric folds and composite Riedel structures along the faults. Despite an apparently uninterpretable tangle of Cretaceous imbricates in map view, down-plunge projections, such as the example below, reveal strikingly planar imbricates which break off the top of both regional and subsidiary culminations. Retrodeformation of the cross-sections is compatible with simultaneous movement on two or more faults. The results are in accord with predictions of the proposed synchronous thrust model.



Nº 4281

OBSERVATION AND MEASUREMENT OF HORIZONTAL TERRAIN DISPLACEMENTS ASSOCIATED WITH THE LANDERS EARTHQUAKE OF 28 JUNE 1992 USING SPOT PANCHROMATIC IMAGERY

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Previously, we speculated that SPOT satellite imagery could be used to measure terrain displacements associated with earthquakes even though such displacements are smaller than the 10m resolution of the imagery (GSA Abs, 1990, v. 22, no. 3, p. 16). The Landers,

California, earthquake provided the first clear opportunity to demonstrate this capability. We acquired an image taken on 27 July 1991, before the earthquake, and had the satellite programmed to acquire a matching scene on 25 July 1992, just 27 days after the quake. These images were taken from the same orbital position and on nearly the same day of year. Thus, problems of differing view and illumination angles were avoided.

Initial results have been very positive. By enlarging corresponding small portions of the images and then alternating them on an image display device, we were able to locate the fault breaks and observe the fault motions (EOS, 1992, v. 73, no. 43, p. 364). By recording such displays for several sites, we produced a video which was widely reported in the media as the first visual observation of fault motion from space (e.g. Denver Post, 8 Dec 92, p. 2). The displays allow analysis of the details of deformation patterns that would otherwise go undetected. In addition to terrain shifts, ground breakage is observable in the images. This results from the darkening of the ground by the internal shadows of numerous cracks over a 10-20 m wide zone, especially as viewed at nadir.

Quantification of the terrain displacements is expected to result in a map of the horizontal strain field of the earthquake at unprecedented levels of spatial detail. The procedure involves computationally demanding statistical image matching performed on a supercomputer (Episodes, 1992, v. 15, no. 1, p. 56-61). Early results are consistent with known fault locations and offsets and appear to show sharp differences among the fault blocks defined by overlapping fault strands. Results are most reliable for rugged bedrock areas that form distinct image patterns. The precision of measurement appears to be about 50 cm for such areas. This is a full order of magnitude finer than the maximum fault offsets and is therefore adequate for mapping patterns within the strain field.

Nº 26436

OXYGEN ISOTOPE IMAGE OF HYDROTHERMAL FLUID FLOW IN THE CON VIRGINIA BONANZA, COMSTOCK LODGE MINING DISTRICT, NEVADA

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The bonanza slope of the Con Virginia and California mines produced 1.4 million tons of ore, containing more than 2.5 million oz of Au and 45 million oz of Ag, during the period 1873 to 1882 (Smith, 1943). The present day value of the precious metal from this single slope would exceed \$1,000,000,000. The slope was as much as 200' wide and 900' long, but was not properly part of the Comstock Lode, a thick silicified zone closely associated with the 45° dipping Comstock fault that separates hanging wall andesites from the 2 km² Davidson granodioritic stock. Rather, the bonanza rooted in the Comstock Lode at the 1750' level, but extended directly upward into the hanging wall to a point 114' above the 1200' level, representing a vertical extent of more than 650'. It is fortunate that G.F. Becker (1882) collected 197 samples of wallrock from the 175' to the 2500' levels of the Con Virginia and California mines, which have been curated by the Smithsonian.

The low whole-rock $\delta^{18}O$ values (+3.8 to -3.8 ‰) of all but 3 of 87 analyzed samples of the propylitized andesites and granodiorites from these mines, and the $\delta^{18}O$ values of quartz (+0.4 to +2.5) and the δD values of fluid inclusions (-97 to -128) from 6 samples of vein materials (Vikre, 1989), all indicate the dominance of meteoric water. Our whole-rock $\delta^{18}O$ values allow construction of a detailed, 3-D image of the pattern of the convective fluid flow. This image clearly shows the intricate and conformable relationship of the bonanza deposit to an equant, ~3000' x 3000' meteoric-hydrothermal gyre that originated in the cooler, surrounding country rocks. The fluid clearly did not originate from the Davidson granodiorite, but rather moved downward and laterally inward toward this stock, and then ascended along and above the Comstock fault and the contact zone of the intrusion, in a pattern typical of buoyancy-driven groundwater flow. A plan map of the whole rock $\delta^{18}O$ values at the Suro Tunnel level (1750'), shows that the upwelling central part of this gyre ($\delta^{18}O = 0$ to +3.8) occupies an area of approximately 300' x 300' and is surrounded on three sides by a semicircular zone of extremely high $\delta^{18}O$ gradients. Beyond this is a zone of lower whole rock $\delta^{18}O$ values (-2.0 to -2.9) that possibly represents a zone of ascent of hotter, deeper circulating groundwater. Thus, the deep Con Virginia bonanza formed in a zone of strongly focused convective flow associated with a short wavelength transverse cell in a far larger meteoric-hydrothermal system.

Nº 4532

PREASSESSMENT OF THE HOLY CROSS QUADRANGLE, WEST-CENTRAL ALASKA

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The preassessment program of the U.S. Geological Survey is a team effort to collect and integrate all available geoscience information on poorly known areas in order to determine what future investigations are needed to evaluate the mineral resource potential of those areas.

Preassessment investigations of the Holy Cross quadrangle were undertaken because the area is one of many in Alaska that still lack adequate geoscience information for resource assessment. To start, a reconnaissance geologic map at 1:250,000 scale, the first ever for the quadrangle, was compiled from unpublished field notes of a number of Survey geologists. The map reveals that bedrock dominantly consists of Tertiary volcanic and some granitic rocks, Cretaceous volcanic and sedimentary rocks, and some ophiolitic rocks of late Paleozoic-early Mesozoic age. Synthesis of geophysical data from the quadrangle resulted in an isostatic residual gravity map, and from NURE data, a magnetic intensity grid map. No geochemical data are available, but some assumptions could be made by projecting the results of resource studies from nearby areas.

On the basis of this newly compiled information, the occurrence of five metallic mineral deposit types are considered possible in the quadrangle. These are: (1) Epithermal Hg-Sb-Au-Ag vein deposits; (2) Au-W vein deposits; (3) Cu-Zn and Cr-Cu-Ni-PGE deposits; (4) Cu-Ag-Sn polymetallic vein deposits; and (5) Skarn deposits.

The Holy Cross preassessment also shows how much useful geoscience information can be obtained for large areas in Alaska by laboriously collecting and synthesizing already available, but dispersed and unprocessed, geoscience data.

where:

C is the concentration of solute;

t is the time;

D is the coefficient of hydrodynamic dispersion;

x is the distance;

v is the velocity of ground-water flow;

S and n are the adsorption isotherm parameters; and,

k is the first-order microbial degradation rate constant.

The primary processes that restrict the spread of hydrocarbons with moving ground water are adsorption and microbial degradation. If the rates of adsorption and degradation are fast relative to the rate of ground-water flow, then hydrocarbons will not be transported far from their source area. Conversely, if the rates of adsorption and microbial degradation are slow relative to ground-water flow, contaminants will be transported from the source area and may discharge at points of contact (POC) such as surface-water bodies. Equation 1 can be solved with finite-element numerical methods to predict concentrations of solutes at particular points in space (such as a POC) at various times.

For the MGP site in Charleston, S.C., equation 1 was solved numerically using the SUTRA code with field- and laboratory-derived rates of adsorption and microbial degradation to simulate the release of naphthalene at the site since the mid-1800's (fig. 1). The simulated plume geometry depicts the current steady-state distribution of naphthalene in the shallow aquifer system. Because the particular POC has been reached (discharge to the Cooper River), the numerical model framework can allow the range of naphthalene concentrations discharging to the Cooper River to be estimated.

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The Effects of Oil-Field Brines on Aquifers—Brine Disposal in the East Poplar Oil Field, Fort Peck Indian Reservation, Northeastern Montana

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Introduction

The U.S. Geological Survey (USGS) currently is investigating the effects of disposal of oil-field brine on shallow ground water in Quaternary alluvial and glacial deposits in the East Poplar oil field, on the Fort Peck Indian Reservation, in northeastern Montana (fig. 1). The study, which is being conducted in cooperation with the Fort Peck Tribes Water Resources Office, began in October 1991 and is scheduled to end in September 1994.

An earlier USGS study (Levings, 1984) documented the existence of brine contamination in shallow ground water along the Poplar River in this area. The present study not only expands on that work but also focuses on brine contamination in glacial till deposits east of the river. The general purpose of this study is to determine the extent, magnitude, and movement of brine in shallow ground water in the East Poplar oil field. Specific objectives are to (1) delineate areas of brine or saline water occurrence and its lateral and vertical extent in shallow ground water; (2) determine probable sources of the brine; (3) determine direction and, if possible, rate of brine movement; (4) determine chemical characteristics of the brine and shallow ground water; and (5) investigate possible effects of brine or saline ground-water discharge on the quality of water in the Poplar River.

Location and Geographic Setting

The East Poplar oil field study area is in the south-central part of the Fort Peck Indian Reservation, in northeastern Montana, a few miles north of the town of Poplar (fig. 1). The study area is traversed by the Poplar River. Land uses are dryland wheat farming, livestock grazing, and oil production. Shallow ground-water supplies are obtained both from alluvial deposits along the Poplar River and from glacial deposits in the uplands east of the river.

Brief History of Oil-Production Activities

Oil production began in 1952 from the Mississippian Madison Group, at depths of about 5,500 to 6,000 feet. Over the past 42 years, millions of barrels of brine (brine is defined by USGS as water containing greater than 35,000 mg/L (milligrams per liter) of dissolved solids) have been produced with the oil.

Brine disposal is by injection into shallower subsurface geologic units, mainly the Upper Cretaceous Judith River Formation, at depths of about 800 to 1,000 feet, and a Lower Cretaceous sandstone, at a depth of about 3,300 feet. Smaller quantities of brine have been directed to storage and evaporation pits. Limited attempts have been made to inject brine back into the producing zones for secondary recovery of oil, but at present (1994) no such activity is occurring.

General Geology

The study area lies along the western flank of the Williston Basin and generally consists of a broad, flat glacial bench that is dissected by the Poplar River valley. The lowest formation that crops out is the Upper Cretaceous Bearpaw Shale, a dark-gray marine shale.

The Bearpaw Shale is overlain by Pleistocene glacial deposits (till) that generally attain a maximum thickness of about 100 to 150 feet. The glacial deposits mainly lie topographically above and to the east of the Poplar River, although less extensive exposures also are present to the west. The glacial till deposits generally consist of a heterogeneous mixture of rock particles ranging in size from clay to boulders. A Pleistocene unit, the Wiota Gravel, probably is present at the base of the till, but does not crop out.

Deposits of Quaternary (Holocene) alluvium are present in the Poplar River valley. Along the flanks of the valley, deposits of Pleistocene and Holocene fan alluvium and colluvium, along with thin deposits of dune sands, are exposed. Thickness of alluvium generally is about 50 feet. Alluvium mainly consists of silt, sand, and gravel from reworked glacial deposits.

General Hydrogeology

Shallow ground-water supplies are obtained from both the alluvial and glacial deposits. Wells completed in alluvium generally range from about 15 to 50 feet in depth. Wells completed in glacial deposits generally range from about 70 to 120 feet in depth.

In alluvium, direction of water movement generally is from north to south along the Poplar River valley, with local flow components toward the river. In glacial deposits, direction of water movement is not completely known; however, in the bench on the east side of the river, flow is generally southwest.

In some areas, handling, transport, and disposal of the brine have resulted in its movement into shallow ground water in both the Poplar River alluvium and the glacial deposits. Probable sources of the brine in the shallow ground-water systems are (1) leakage of water through breaches in disposal-well casing; (2) leakage of water through storage and evaporation pits that either were not adequately sealed initially or that have developed ruptures in

the sealing material; and (3) leakage of water from brine-transporting pipelines.

Preliminary Results

Field work for the project is complete. Data collection consisted of conducting electromagnetic surface-geophysical traverses; monitor-well drilling and completion; water-quality sampling of monitor wells, selected domestic wells, and brine-disposal wells; and obtaining streamflow and water-quality measurements along the Poplar River.

Electromagnetic Surface Geophysics and Monitor-Well Drilling

Electromagnetic surface-geophysical methods were used to assist in delineating areas of brine or saline water occurrence and to assist in locating sites for drilling and completing monitor wells. Approximately 7,000 electromagnetic measurements were made during 1992 and 1993. Twenty-seven monitor wells have been completed; 19 wells are completed in alluvium and 8 in glacial deposits. For each well (with the exception of two nested monitoring well sites), an attempt was made to bottom the hole in the Bearpaw Shale to obtain a total thickness for the deposit at that locality.

Two aquifer tests (one of alluvium using a pumped well and three observation wells, and one of glacial deposits using a pumped well and two observation wells) were conducted in 1993. The tests were conducted beyond salinity-plume areas to obtain data about ground-water flow directions and rates, and hydrologic characteristics of the deposits.

Water-Quality Sampling of Wells

Water-quality sampling is complete for all monitor wells, selected domestic wells, and brine-disposal wells. Wells were sampled for major and trace constituents. Dissolved-solids concentrations of the brine are as much as 160,000 mg/L, the major constituents being chloride and sodium. In plume areas, dissolved-solids concentrations in shallow ground water are as much as 114,000 mg/L, and the major constituents also are chloride and sodium. In non-plume areas, dissolved-solids concentrations in shallow ground water typically are less than 2,000 mg/L, and the major constituents are bicarbonate and sodium.

Streamflow and Water-Quality Measurements

Four sets of streamflow and water-quality measurements were conducted along a 6-mile reach of the Poplar River to determine gains or losses in flow and changes in water quality. In the first set of measurements, conducted during September 1981 (Levings, 1984), streamflow varied from 1.7 ft³/s (cubic feet per second) upstream to 0.74 ft³/s

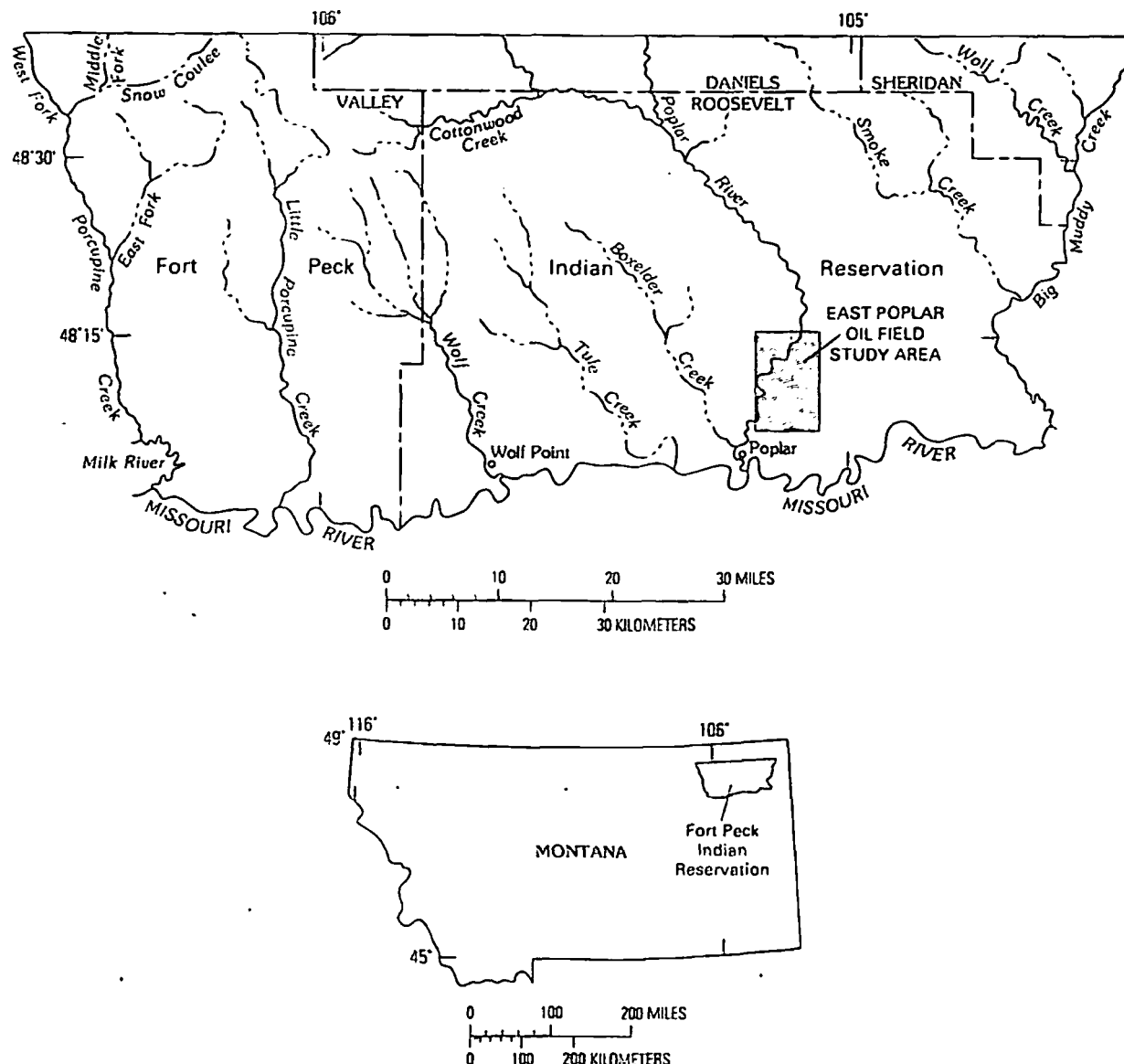


Figure 1 (Craig and Thamke). Location of East Poplar oil field study area, northeastern Montana.

downstream; chloride concentration increased from 20 to 880 mg/L. In the second set of measurements (conducted during April 1991), streamflow varied from 82 to 85 ft³/s; chloride concentration increased from 11 to 29 mg/L. In the third set of measurements (conducted during July 1991), streamflow varied from 47 to 44 ft³/s; chloride concentration increased from 10 to 61 mg/L. In the fourth set of measurements (conducted during September 1991), streamflow varied from 8 to 1 ft³/s; chloride concentration increased from 17 to 160 mg/L.

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Potential Impact of Oil and Gas Drilling Operations on Carlsbad Caverns National Park, New Mexico

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Studies of rock fracture and jointing trends, combined with gas geochemistry techniques, have provided some preliminary tools for evaluating the potential impact of oil and gas drilling operations on Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico. Lechuguilla Cave is now widely held to be the world's finest speleological resource and is considered by many experts to be a veritable treasure-trove of underground scientific research opportunities. In addition to containing more elemental sulfur and secondary gypsum than all other known limestone caves in the world combined, Lechuguilla possesses an array of new speleothem types, curious mineralogic associations, and a unique bacterial and fungal microflora that is a focus of cancer research and of NASA-sponsored exobiological (the study of extraterrestrial organisms) research.

The question of whether or not high-permeability pathways exist between the extensive passageways of Lechuguilla (more than 120 km of passage have been mapped since 1986) and prospective oil and gas drilling sites (located less than 1.25 km north of the cave on Bureau of Land Management property) was addressed by investigating the relationships between rock fracture/jointing trends and cave parameters (location, amount of passage, and predominant trend of passages), and by tracer-gas experiments. Lineaments and curvilineaments (structurally controlled straight or curving lines visible on aerial photographs) were interpreted from satellite and high-altitude aircraft imagery and plotted with the cave data at a scale of 1:24,000. For most caves, and particularly for Lechuguilla, more than 90 percent of the known cave passageways spatially coincide with the trend of the photolineaments. Statistically significant trends were also documented from fractures and joints mapped from outcropping rock pavements, and from microscopic examination of rock thin sections. The results indicate that preexisting structural features exerted a strong influence on sites of cave development. Every cave in the area appears to be associated with a lineament, but not every lineament can be shown to be associated with a cave, although the probability of coincidence is high. Previously drilled gas wells that occur on interpreted lineaments exhibit a uniform high frequency of lost fluid circulation within the 650-m-thick cavernous rock package (fig. 1; p. 100-101). Most of these zones of fluid loss directly correlate to discrete levels of passage development in Lechuguilla Cave. In 1991 a large passage was discovered in Lechuguilla that extended along a mapped, northwest-oriented lineament toward the area of the BLM-managed drill sites. Approximately 8.1 m³ of helium gas was released in the cave near the new passage and more than 40 1-m-deep soil-gas probes were installed on the surface at lineament intersections in order to detect helium migrating out of the cave system. Approximately 90 days after the initial gas release, significant amounts of helium were recovered from a probe placed directly on the northwest-trending lineament an 150 m from the Sidewinder gas well. The helium had moved to the recovery site at nearly 2 cm/min, a rate slightly greater than that of normal helium diffusion. The data do not provide any information on the size of the gas-transmitting cave passage but do confirm that a permeable pathway exists between the two sites. Future work should focus on refining photolineament interpretation, accumulating additional ground-truth for mapped lineaments, and monitoring the ambient cave environment in order to detect the possible introduction of drilling contaminants, and to a greater degree, the presence of common constituents in the produced gas, specifically methane and hydrogen sulfide.

By Tim Brunson
Murphy Oil USA, Inc.
El Dorado, Arkansas
March, 1985

GENERAL FIELD DATA

Regional Setting:

High plains, steppe/Williston Basin Area.

Surface Formations and Elevation:

Glacial Till and Bearpaw Shale (Upper Cretaceous),
2,000'-2,200'

Discovery Well and Date:

EPU No. 1, SW NE Sec. 2, T28N-R51E, TD 9,163', 3-10-52.

Exploration Methods:

A combination of seismic and surface geology was used to determine the location of the discovery well.

Oldest Horizon Penetrated:

Ordovician Winnipeg Sandstone.

Horizons with Shows:

Principal production is from the "B" zone of the Charles Formation (Mississippian), but there is also production from the "A" and "C" zones of the Charles Formation, also from the Heath Formation (Mississippian), and the Nisku Formation (Devonian).

Nature of Trap:

Principally structural, but stratigraphically influenced.

Area of Trap:

Approx. 18,000 productive acres.

No. of Producing Wells: 45

Abandoned Wells: 15, Three of these are now water disposal wells.

Shut In/Temp Abdn Wells: 41

Disposal/Injection Wells: 6

Dry Holes: 12

Major Operators:

The Poplar East Unit is operated by Murphy Oil USA, Inc. The working interest partners include Fairway Resources, Inc., Phillips Petroleum, Inc., Exxon Company USA, TPEX Exploration, Inc., Munoco Company, and C.F. Lundgren. The major offset operator is Grace Natural Resources.

Drilling and Casing Practices:

Drill through pay zones and set pipe to TD, then perforate the productive horizon(s) and acidize if necessary.

Logging Suite:

Generally, Electric Logs and Micro-Logs, but some Sonic

Logs and Gamma Ray-Neutron Logs.

Testing Practices:

Drill Stem Tests, Coring, and Cased Hole Production Tests.

Market:

During the 33 year history of the Poplar East Field, the production has been marketed in a number of ways. It has been transported to various refineries via the Butte Pipeline, railroad tank cars, and the Wascana Pipeline. The oil is presently being trucked to the Kenco Refinery in Macon, Montana.

POPLAR, EAST FIELD

(See map in pocket)

T.28&29 N., R.50,51,52 E.
Roosevelt County, Montana

RESERVOIR DATA

Producing Formation:

Principal production is from the "B" zone of the Charles Formation, but there is production from the "A" and "C" zones of the Charles Formation. There has also been Heath Formation production from two wells, and Nisku Formation production from one well.

Lithology, Continuity, Thickness:

The Charles Formation is consistent over the entire field, but porosity and permeability, along with connate water varies to some extent. The average gross thickness of the "A", "B" and "C" zones are 80', 145' and 70' respectively.

Avg. Depth (& MSL):

The average depth of the "B" zone of the Charles Fm. (principal production) is 5,684' (-3,567' MSL).

Porosity/Permeability:

Average porosity is approx. 12%. Average matrix permeability is approx. 8 md. Production capability is heavily influenced by fractures.

Oil, Gas Column: (Water Contact MSL):

An exact oil/water contact is difficult to define due to the wide spacing of the wells, stratigraphic variations, and hydrodynamic tilt. It is approx. (-3,350') on the south edge of the field and (-3,700') on the northeast edge of the field (based on the B-1 Structure Map). There is an apparent tilt approx. 18-20' per mile in a northerly direction.

Avg. Net Pay Thickness:

25'

Area this Reservoir:

Order/Docket No. and Spacing Details:

Unitized in 1985, Order No. 7-55. Originally, the unit was drilled on 160 acre spacing, with wells being located in the center of the SW/4 of each quarter section. However, offset operators followed a 40 acre spacing pattern, and the unit drilled irregular locations to meet offset requirements. Also, some infield drilling on the north end of the unit has reduced the spacing in the area to 80 acres.

BO/MCF Per Acre-Foot:

545 BO/AF

Drive Mechanism:

Volumetric water drive.

Character of Oil/Gas:

Avg. oil gravity for all zones is 40.7 degrees API @ 60 degrees F.

Gas-Oil Ratio:

20

Water Rw, Salinity:

Rw is approx. 0.065 ohm-meters. Chloride as NaCl avgs. 150,000 ppm.

Avg. Saturation:

Approx. 30% connate water saturation.

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**GEOLOGY AND GROUNDWATER RESOURCES IN THE VICINITY OF THE EAST
POPLAR OIL FIELD, FORT PECK INDIAN RESERVATION, MONTANA**

by

**Kenneth A. Phillips, PG - Groundwater Specialist, See Employee
United States Environmental Protection Agency, Region VIII**

July, 1999

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1.0 Introduction

1.1 Purpose and Scope

This report summarizes the groundwater and hydro-geologic conditions in the immediate area of the East Poplar oil field, Fort Peck Indian Reservation, Montana. The study area is shown in Figure 1. The information and data presented here is a compilation of published efforts and investigations of many individuals and organizations both State and Federal. Without their efforts this report would have been impossible.

This report's objectives are:

To present all information regarding groundwater occurrences, geology, geologic controls, aquifers and general water quality in the geographic area covered by this report.

1.2 Important and Relevant Geologic and Groundwater Investigations and Publications

Bibliography?
Smith (1910) is credited as being the first to investigate and publish geologic information followed by Collier and Thom in 1918, Alden (1932), Colton and Bateman (1956), Witkind (1959), Howard (1958, 1960). Important geologic papers and groundwater maps have been published by Colton and others (1961), Levings (1984), Jensen and Varnes (1964), Bergantino (1986) and (1987), and Thamke and Craig (1997).

Important groundwater papers and maps featuring alluvial aquifers and glacial deposits within the Missouri River valley area were published by Swenson (1955), Hopkins and Tilstra (1966), Hamke and others, (1966), Donovan and Bergantino (1987), Thamke, Craig and Mendes (1996), and Thamke and Craig (1997). The last two are considered as probably the most important and informative as they contain very detailed information regarding groundwater supplies, abundance and qualitative information.

1.3 Physiography

The southeastern part of the Fort Peck Indian Reservation is located within the Great Plains region that covers all of eastern Montana. The Fort Peck area contains four (4) distinct topographic settings:

- 1) alluvial valleys associated with the Missouri, Milk, Poplar and Big Muddy rivers and their tributaries
- 2) unglaciated, upland terraces underlain by alluvial sands and gravels of Flaxville or younger geologic age
- 3) gently undulating to irregular or dissected highlands with bedrock exposed or at shallow depth
- 4) gently undulating to rolling highlands underlain by glacial till

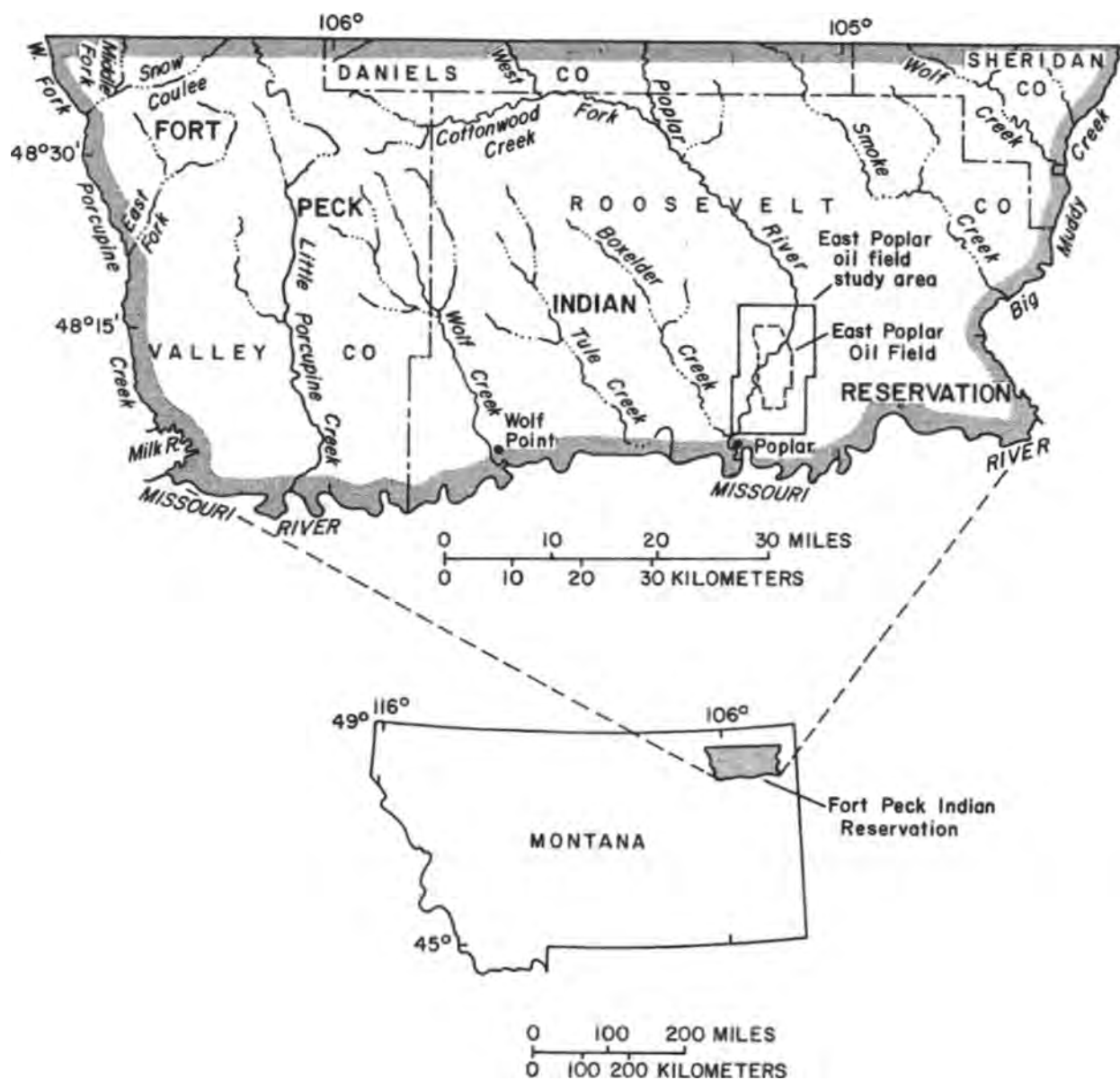


Figure 1. Location of the East Poplar oil field study area, northeastern Montana from: Thamke and Craigg (1997)

The drainage pattern and flow direction of tributaries to the Missouri river are generally southeast-flowing and dendritic in pattern. Major tributaries of the Missouri are the Big Muddy, Milk and Poplar. All of the major valleys have been glaciated and filled with alluvial and glacial sediment, their widths range up to four (4) miles.

2.0 Regional Geology

2.1 General Geology

The study area is located within the western part of the large, hydrocarbon-rich Williston Basin (Figure 2). The basin is one of the largest hydrocarbon-bearing and producing basins in North America. It's size is approximately five (5) hundred miles in length and three (3) hundred miles in width. The area of concern covered by this report is the East Poplar Field, a part of the Poplar Dome, located in the western part of the Williston Basin (Figure 2) and immediately north of the town of Poplar, Montana.

The East Poplar Field was discovered in October, 1952 by Murphy Oil Company by the EPU No. 1 well located in the SWNE of Section 2, Township 28 north, Range 51 east.

Thamke and Craigg (1997) The principal geologic formations exposed in the area are the Upper Cretaceous BearPaw Shale, Hell Creek Formation, and Fox Hills Sandstone; Tertiary Flaxville and Fort Union Formations; Quaternary glacial and related deposits; and Quaternary alluvium deposits (Figure 3).

2.2 Quaternary or Recent Deposits

Thamke and Craigg (1997) said that Quaternary units in the study area include Wiota Gravel, Sprole Silt, glacial till, fan alluvium and colluvium, and alluvium. Minor thicknesses and extents of glacial outwash, lake deposits, and dune sand also are present, but are not discussed separately in this report.

Pleistocene Wiota Gravel consists of unconsolidated deposits of clay, silt, and quartzitic sand and gravel. Thickness in the study area is uncertain, but Colton (1963a, b) reported a maximum thickness of 55 feet to the south of the study area.

Pleistocene Sprole Silt overlies the Wiota Gravel and consists of poorly bedded to massive deposits of silt. Colton (1963 a, b) reported a thickness a maximum thickness of 100 feet for the Sprole Silt to the south of the study area.

Pleistocene glacial till is a complex, unstratified, and heterogeneous admixture of clay, silt, sand, gravel, and boulders deposited by glaciers. Colton (1963a,b) reported that thickness generally is about 15 feet, but locally may be as much as 250 feet. In the study area, till is present mainly beneath the topographic bench east of the Poplar River.

Thamke and Craigg continue saying that Pleistocene and Holocene fan alluvium and colluvium underlies flood plains and consists of slope-wash deposits derived from topographically

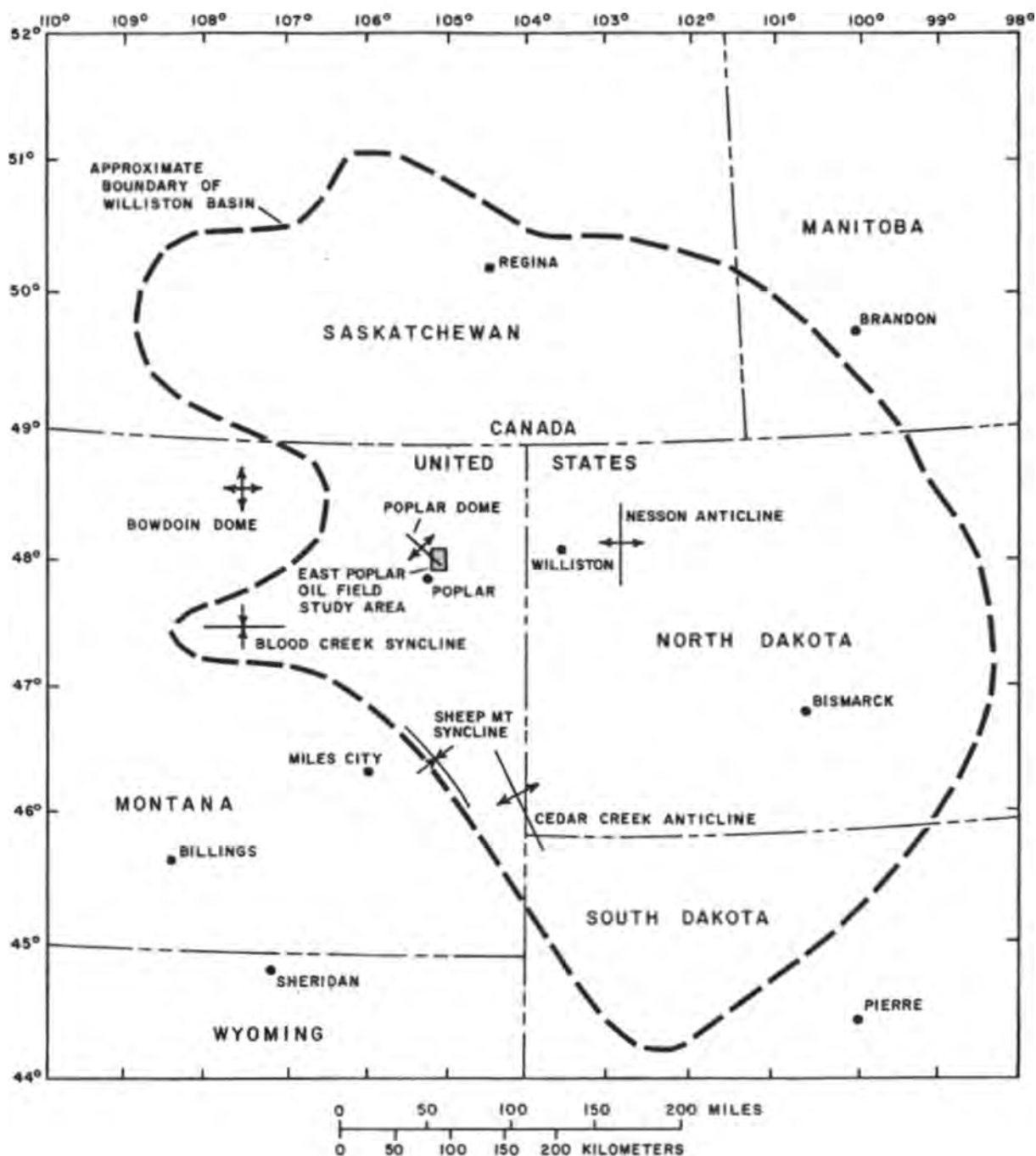


Figure 2. Location of Williston Basin, major structural features, and East Poplar oil field study area from: Thamke and Craig (1997)

Generalized stratigraphic column for the Montana part of the Williston Basin
(Modified from Balster, 1980, and Rice, 1976a)

Erathem	System	Series	Geologic unit		
Cenozoic	Quaternary	Holocene	Alluvium	Fan alluvium and colluvium, dune sand	
		Pleistocene	Glacial deposits, Sprole Silt Wooten Gravel		
	Tertiary	Pliocene	Flaxville Formation		
		Paleocene	Fort Union Formation		
Mesozoic	Cretaceous	Upper Cretaceous	Hell Creek Formation		
			Montana Group	Fox Hills Sandstone	
				Bearpaw Shale	
				Judith River Formation	
				Claggett Shale	
				Eagle Sandstone	
				Telegraph Creek Formation	
				Colorado Group	Niobrara Formation
			Carlisle Shale		
			Greenhorn Formation		
			Belle Fourche Shale		
			Mowry Shale		
			Newcastle Sandstone		
			Skull Creek Shale		
			Fall River Sandstone		
		Lower Cretaceous	Fuson Shale		
			Lakota Formation		
			"Dakota Sandstone"		

Erathem	System	Series	Geologic unit	
Mesozoic	Jurassic	Upper Jurassic	Morrison Formation	
		Middle Jurassic	Ellis Group	Swift Formation
				Riordan Formation
				Piper Formation
	Nesson Formation			
Triassic				
Paleozoic	Permian		Spearfish Formation	
			Minnekahta Limestone	
			Opeche Formation	
	Pennsylvanian		Minnelusa Sandstone	
			Tyler Formation	
	Mississippian		Big Snowy Group	Heath Formation
				Otter Formation
				Kibbey Sandstone
			Madison Group	Charles Formation
	Mission Canyon Limestone			
Lodgepole Limestone				
Devonian, Silurian, Ordovician, and Cambrian rocks, undivided			Sedimentary rocks consisting of sandstone, siltstone, shale, limestone, and dolomite	
Precambrian			Crystalline igneous and metamorphic rocks	

Figure 3. Stratigraphic chart of geologic formations in the study area from: Thamke and Craig (1997)

higher deposits; lithologically the slope-wash deposits are similar to Holocene alluvium. These deposits are not vertically extensive; Colton (1963a, b) reported that the maximum thickness is 20 feet. Laterally, however, these deposits can be more than 1 mile wide, although the average width is much smaller.

Holocene alluvium consists of stream-deposited clay, silt, sand, and gravel. The sand and gravel deposits typically occur as lenses of varying thickness. Detailed lithologic descriptions for 19 USGS monitoring wells completed in alluvium along the Poplar River are given in Thamke and others (1996), table 3).

Thamke and Craigg (1997) say that the Pleistocene Wiota Gravel, Sprole Silt, glacial till, and dune sand are undifferentiated and are referred to as "glacial deposits". Pleistocene and Holocene fan alluvium and colluvium and Holocene alluvium are undifferentiated and referred to as "alluvium". Lithologic logs from eight USGS monitoring wells drilled during the investigation indicated that the combined thickness of glacial deposits in the study area ranges from at least 56 to about 100 feet. The combined thickness of alluvium ranges from 22 to 56 feet throughout the Poplar River valley. Colton (1963a, b) reported that, in the vicinity of the study area, thickness of these deposits averages about 50 feet; Leving (1984, table 3) gave a range of thickness of 43 - 54 feet. Lithologic logs from monitoring wells drilled during the investigation indicated that, in most places, alluvium ranges in thickness from about 32 to 52 feet; a thickness of 22 feet, reported in USGS monitoring well FPB92-14 (located in NE1/4SE1/4NW1/4NE1/4 sec 21, T.29N; R51W.) Indicates a local subsurface high of the Bearpaw Shale.

2.3 Pre-Glacial Missouri River Drainage

Donovan and Bergantino (1987) said that there is good evidence that, in Pleistocene time before glaciers entered Montana, the Missouri River flowed northeast from this part of Montana into North Dakota and Saskatchewan, eventually draining into Hudson Bay. The river at that time occupied a different course than today in two locations: upstream from Wiota, where it flowed in the modern Milk River valley, and downstream from Poplar, where it flowed in a currently abandoned and buried northeast-trending channel to the Montana-North Dakota border near Grenora, North Dakota, and beyond.

This buried preglacial channel within the reservation area occupies a linear depression carved into bedrock between Poplar and Homestead, cut to below an elevation of 1800 feet by fluvial erosion in early to mid-Pleistocene time. The depression was cut during a series of at least 5 erosion-alluvium cycles. During each of these cycles, an erosion bench was first cut, then subsequently overlain by a bed of alluvial sand and gravel up to 30 feet thick. The tops of these alluvial terraces are nearly level. Successive erosion cycles cut progressively deeper into the Pleistocene and Cretaceous bedrock which underlies this area. Successively younger terrace levels are progressively lower in elevation.

3.0 Regional Hydrogeology

3.1 Major Aquifers

Thamke and Craigg (1997) The Quaternary deposits are the sole developed source of ground water for residents of the study area. In general, wells completed in Quaternary deposits provide sufficient yields and, in uncontaminated areas, potable water for domestic purposes. Few wells are completed below the Quaternary deposits because of the lack of water in the underlying Upper Cretaceous Bearpaw Shale which is 700 - 1,000 feet thick.

Thamke and Craigg said that water in Quaternary deposits occurs mainly under unconfined (water table) conditions, although locally, conditions are semiconfined due to the heterogeneity of clays, silts, sands, and gravels. Depth to water below land surface in the study area generally ranges from about 5 to 44 feet in alluvium and about 7 to 139 feet in glacial deposits. Fresh water in the Quaternary deposits in the study area is recharged by infiltration of precipitation, streamflow, and fresh water movement from upgradient areas. Water in the Quaternary deposits is discharged by streamflow, evapotranspiration, springs, and water withdrawals. generalized potentiometric surface and direction of ground-water movement in Quaternary deposits are shown in figure 6 (pl. 1), Thamke and Craigg (1997). The altitude of static water level in 190-93 ranged from about 1,950 to 2,060 feet above sea level. Water in Quaternary deposits east of the Poplar River generally moves westward toward the river where it merges with southward-flowing ground water in the Poplar River valley. Downward movement of water from Quaternary deposits into the underlying Bearpaw Shale probably is not significant because of the relatively impermeable nature of the Bearpaw; downward movement of water from Quaternary deposits into the Bearpaw probably occurs only locally to shallow depths, where minor fractures are present in the upper, eroded surface of the Bearpaw.

3.2 Ground Water Quality

Attempting to write intelligently about this subject is difficult if not impossible because the only investigation conducted in the area of study was conducted by Thamke and Craigg and published by the United States Geological Survey in 1997. I have chosen to present their work in entirety herein to preserve accuracy.

Thamke and Craigg (1997) The quality of water in Quaternary deposits in the study area is highly variable and is dependent on location relative to sources of contamination. Dissolved solids, reported in milligrams per liter, is the sum of all dissolved constituents in the water and is predominantly composed of the major ions in solutions. Sodium, bicarbonate, and chloride are the dominate ions in water from most wells completed in the Quaternary deposits. Of these dominant ions, only chloride generally exhibits a conservative behavior and generally is present in natural water at low concentrations. Therefore, concentrations of dissolved solids and chloride ions are used in this investigation to classify types of ground water.

The EPA has established regulations and standards for public drinking-water supplies. These regulations and standards are not used to regulate the quality of water produced from individual privately owned wells, but to serve as guidelines with which to evaluate the water

quality. Primary Drinking-Water regulations are not established for dissolved solids and chloride. However, Secondary Drinking-Water Standards specify SMCL's of 500 mg/L for dissolved solids and 250 mg/L for chloride. Dissolved-solids concentrations in water sampled during 1989-93 from wells completed in the Quaternary deposits ranged from 427 to 91,100 mg/L; 26 of the 27 privately owned wells contained water with dissolved-solids concentrations that exceed the SMCL. Chloride concentrations in water sampled during 1989-93 from wells completed in the Quaternary deposits ranged from 7.3 to 58,000 mg/L; 15 of the 27 privately owned wells contained water with chloride concentrations that exceed the SMCL.

On the basis of dominant ions and dissolved-solids concentrations, Leving (1984) identified three principal water-quality types from alluvium in the Poplar River valley; a fourth water-quality type, representing the actual brine produced with the crude oil, also was identified. Distinguishing characteristics of the four water types are:

Type 1 water is not dominated by the chloride anion and dissolved-solids and chloride concentrations are similar to water in Quaternary deposits in other parts of the reservation;

Type 2 water is dominated by the chloride anion and the chloride concentration range typically is 330-4,800 mg/L;

Type 3 water is dominated by the chloride anion and the chloride concentration is typically greater than 5,200 mg/L;

Type 4 water is actual samples from brine-injection wells. These general water types have been defined in greater detail for this investigation and provide a useful classification to describe water-quality variability within the current study area.

Type 1 water from wells completed in the Quaternary deposits is located in the northern and southern thirds of the study area and represents the uncontaminated water quality (figure). The chemical composition of Type 1 water ranges from a sodium bicarbonate to a sodium sulfate, with a few instances of magnesium sulfate, magnesium bicarbonate, or calcium bicarbonate chemical compositions. The dissolved solids and chloride concentrations of Type 1 water range from 427 to 2,680 mg/L and 7.3 to 260 mg/L, respectively (table 1). Privately owned wells completed in the Quaternary deposits with Type 1 water are used for drinking-water supply.

Type 2 water from wells completed in the Quaternary deposits is located in various parts of the study area and represents natural ground water that has been moderately contaminated by brine (figure). The chemical composition of Type 2 water is sodium chloride. The dissolved-solids and chloride concentrations of Type 2 water range from 1,170 to 8,860 mg/L and 330 to 4,800 mg/L, respectively (table 1). Privately owned wells completed in Quaternary deposits containing Type 2 water generally are not used for drinking-water purposes, because the large dissolved solids and chloride concentrations make the water unpalatable.

Type 3 water wells completed in the Quaternary deposits is located in two locations - one near the center and one near the southwest quarter of the study area. Type 3 water represents ground water that has been considerably contaminated by brine. The chemical composition of

Type 3 water principally is sodium chloride with a few cases of magnesium chloride. The dissolved-solids and chloride concentrations in Type 3 are much larger than Type 2 water, ranging from 10,100 to 91,000 mg/L and 5,200 to 58,000 mg/L, respectively. Privately owned wells completed in Quaternary deposits containing Type 3 water were used in the past for domestic purposes, but are now unused for any domestic purpose.

Type 4 water, which is very similar to Type 3 water, represents the actual brine that is disposed into brine-injection wells. The chemical composition of Type 4 water is sodium chloride. The dissolved-solids and chloride concentrations in brine range from 47,700 to 201,000 mg/L and 27,000 to 120,000 mg/L, respectively.

3.3 Saline-Water Contamination

Thamke and Craigg (1997) The water-quality data collected from existing wells and surface-water sites confirm the presence of saline-water contamination in the Quaternary deposits and the Poplar River; however, the distribution of the wells alone was insufficient to determine lateral extent of contamination. To determine the lateral extent of the saline-water contamination, data from the electromagnetic geophysical survey were interpreted in conjunction with the water-quality information for existing wells that were drilled subsequent to the electromagnetic geophysical survey. The vertical extent of saline-water contamination was interpreted from the water-quality information at sites that contained both shallow and deep wells. The magnitude of saline-water contamination was interpreted from the ground-water quality data and hydraulic characteristics information. The movement of saline-water contamination was interpreted from ground-water hydraulic gradients, as historical ground-water-quality information. Streamflow and water-quality data for the Poplar River were interpreted in conjunction with ground-water-quality data to determine the effects of saline-water discharge on the Poplar River. The specific source areas of saline-water contamination were determined from the electromagnetic geophysical data and the locations of probable sources of contamination shown on plate 3.

3.4 Contamination in the Quaternary Deposits

Thamke and Craigg (1997) The Quaternary deposits contain salinity levels representative of uncontaminated, moderately contaminated, and considerably contaminated water. Leving (1984) determined that saline contamination of the alluvial aquifer was from brine associated with oil production. Information collected during this investigation indicates that the lateral extent of saline contamination in the alluvial and glacial deposits is substantial, and that at least one specific source may still be contributing brine to the Quaternary deposits.

3.5 Lateral Extent

Thamke and Craigg (1997) The lateral extent of saline-water contamination in the Quaternary deposits may be as much as about 12.4 square miles (plate 3). This extent is within the boundary of the electromagnetic geophysical survey and is estimated on the basis of water-quality data and the electromagnetic apparent conductivity delineation of subareas 2 and 3 in figure 16. Small parts of subarea 1 that contain one or more water wells that produce Type 2 water are considered parts of confirmed saline-water plumes; subareas 2 and 3 that contain one or more

water wells that produce Type 2 or Type 3 water are considered saline-water plumes; subareas 2 and 3 that do not contain water wells are considered possible saline-water plumes; and parts of or the entirety of subareas 2 and 3 that contain one or more water wells that produce Type 1 water are not considered saline-water plumes. The saline-water plumes are defined as Type 2 or Type 3m depending on the type of water derived from wells completed in these areas. The extent and number of plumes are discussed in relation to available water-quality information from sampled wells.

The collective lateral extent of confirmed Type 2 saline-water contamination in the Quaternary deposits is 5.3 square miles (plate 3) Four Type 2 saline-water plumes were confirmed. The northernmost confirmed Type 2 saline-water plume has an area of less than 0.1 square miles and is located in the southwestern part of Section 16, T.29 N; R. 51 E. The second confirmed Type 2 saline-water plume has an area of 0.2 square miles and is located in the eastern part of Sec. 20, T. 29N; R. 51 E. The third confirmed Type 2 saline-water plume has an area of 0.8 square miles and is located in Secs. 19,20,29,30 and 31, T. 29 N; R. 51 E. The southernmost, and largest, confirmed Type 2 saline-water plume has an area of 4.3 square miles and is located in the southern part of Sec. 3 and parts of Secs. 9,10, 15, 16, 17, 20, 21, 22, 27, and 28, T. 28 N; R. 51 E.

3.6 Vertical Extent

The vertical extent of saline-water contamination in the Quaternary deposits is controlled by permeability and porosity and the density of saline water. Since saline water has a greater density than fresh water it tends to migrate over time and distance from its source, primarily down-gradient as well as to the lower parts of the Quaternary deposits. It is doubtful that saline-water contamination has entered the underlying Bearpaw Shale due to its very limited ability to transmit a fluid. The exception would be where the formation has been subjected to fracturing and/or expansion in its upper surface especially at shallow depths.

Thamke and Craigg (1997) have said that subsurface sources of saline water may result in deeper saline water being overlain by fresh water. Likewise, a long-term surface or shallow subsurface source that is still contributing saline water to the aquifer may be indicated by the presence of dense, saline water throughout the aquifer. A recent, nearby source (at any depth) may be indicated by vertical stratification of chloride and density, whereas an older, distant source may be indicated by either a lack of stratification due to dilution and dispersion or a vertical stratification where chloride concentration and water density increase with depth due to downward migration of dense, saline water.

3.7 Magnitude of Contamination

Thamke and Craigg (1997) said that the magnitude of the amount of water in the Quaternary deposits of the study area that is possibly affected by saline water contamination ranges from about 9 to 60 billion gallons (27,600 - 184,000 acre feet). This volume is based on estimates of the saturated thickness of the Quaternary deposits for the lateral extent of confirmed and possible Type 2 and Type 3 saline-water contamination plumes and the porosity of the Quaternary deposits. The saturated thickness of the Quaternary deposits ranges from 17 to 46

feet, the lateral extent of the confirmed and possible Type 2 and Type 3 saline-water contamination plumes is 12.6 square miles.

Thamke and Craigg (1997) continue saying that contaminated water in Quaternary deposits east of the Poplar River generally moves westward toward the river then southward in the Poplar River valley. The variation in water density from saline-water contamination in the Quaternary deposits may result in a significant downward vertical component of flow for the more dense contaminated water. Factors that may affect the vertical density gradients of contaminated ground water may include the source of saline-water contamination (surface or subsurface) and the timing of saline-water contamination (a distinct vertical density gradient may have developed from an older saline-water contamination event, whereas little or no vertical density gradient may have developed from a recent or current saline-water contamination event). In isolated areas, dense, saline water may settle in small depressions on the surface of the Bearpaw Shale.

Thamke and Craigg (1997) have said that possible sources of the brine and resultant saline-water contamination in the Quaternary deposits in the study area are brine injection wells, oil-production wells, brine-evaporation pits, pipelines, storage tanks, and upward brine migration from subsurface zones through well casing or fractures, although no faults or fracture systems are known in the study area.

Characteristics of water types and correlation of electromagnetic apparent conductivity used to delineate saline-water plumes in Quaternary deposits in the East Poplar oil field study area

[Abbreviations: Cl, chloride; HCO₃, bicarbonate; Mg, magnesium; Na, sodium; SO₄, sulfate; mg/L, milligrams per liter; mmho/m, millimho per meter; mi², square miles; N/A, not applicable; 10V, 10-meter, vertical-dipole orientation; 20H, 20-meter, horizontal-dipole orientation; 20V, 20-meter, vertical-dipole orientation; 40H, 40-meter, horizontal-dipole orientation. Symbols: ≥, greater than or equal to; <, less than]

Water type	Water use	Major ions	Dissolved-solids concentration range (mg/L)	Chloride concentration range (mg/L)	Electromagnetic apparent conductivity in Area 1 (fig. 11 and 12, pl. 2)	Electromagnetic apparent conductivity in Area 2 (fig. 13 and 14, pl. 2)	Subarea designation (fig. 16, pl. 1)	Saline-water plume type (pl. 3)	Areal extent within geo-physical survey (mi ²)
Type 1—Uncontaminated	Suitable for most domestic purposes.	Na-HCO ₃ , Na-SO ₄ , Mg-SO ₄ , Mg-HCO ₃ , Ca-HCO ₃	427-2,680	7.3-260	< 40 mmho/m (10V) or < 60 mmho/m (20H)	< 40 mmho/m (20V) or < 60 mmho/m (40H)	Subarea 1—low electromagnetic apparent conductivity	N/A	9.2
Type 2—Moderately contaminated ground water	Suitable for some domestic purposes; generally not used for drinking water.	Na-Cl	1,170-8,860	330-4,800	≥ 40 mmho/m (10V) and ≥ 60 mmho/m (20H); exclusive of subarea 3	≥ 40 mmho/m (20V) and ≥ 60 mmho/m (40H); exclusive of subarea 3	Subarea 2—moderate electromagnetic apparent conductivity	Type 2	7.6
Type 3—Considerably contaminated ground water	Unsuitable for any domestic purpose.	Na-Cl Mg-Cl	10,100-91,100	5,200-58,000	≥ 50 mmho/m (10V) and ≥ 70 mmho/m (20H)	≥ 50 mmho/m (20V) and ≥ 70 mmho/m (40H)	Subarea 3—high electromagnetic apparent conductivity	Type 3	5.0
Type 4—Brine (from oil production)	N/A	Na-Cl	47,700-201,000	27,000-120,000	N/A	N/A	N/A	N/A	N/A

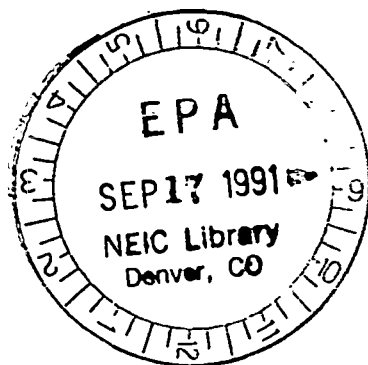
Table 1 from: Thamke and Craig (1997)

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Basic Ground-Water Hydrology



United States
Geological
Survey
Water-Supply
Paper 2220

Prepared in
cooperation with the
North Carolina
Department of Natural
Resources and
Community Development



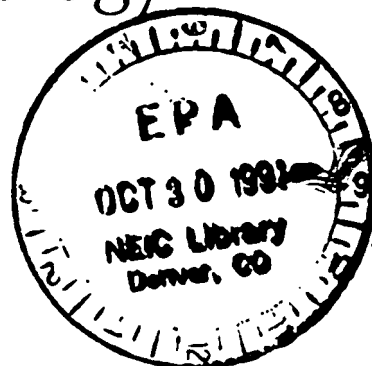
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Basic Ground-Water Hydrology

By RALPH C. HEATH

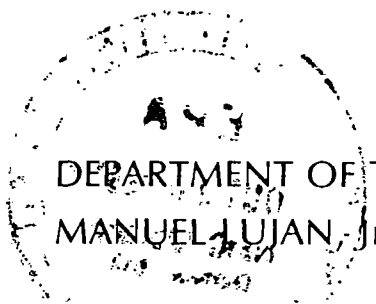
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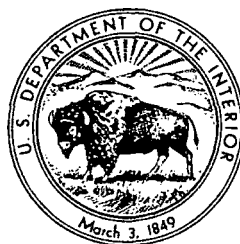
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Basic Groundwater Hydrology:
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DEPARTMENT OF THE INTERIOR
MANUEL LUIJAN, Jr., Secretary
U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director



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PREFACE

Ground water is one of the Nation's most valuable natural resources. It is the source of about 40 percent of the water used for all purposes exclusive of hydropower generation and electric powerplant cooling.

Surprisingly, for a resource that is so widely used and so important to the health and to the economy of the country, the occurrence of ground water is not only poorly understood but is also, in fact, the subject of many widespread misconceptions. Common misconceptions include the belief that ground water occurs in underground rivers resembling surface streams whose presence can be detected by certain individuals. These misconceptions and others have hampered the development and conservation of ground water and have adversely affected the protection of its quality.

In order for the Nation to receive maximum benefit from its ground-water resource, it is essential that everyone, from the rural homeowner to managers of industrial and municipal water supplies to heads of Federal and State water-regulatory agencies, become more knowledgeable about the occurrence, development, and protection of ground water. This report has been prepared to help meet the needs of these groups, as well as the needs of hydrologists, well drillers, and others engaged in the study and development of ground-water supplies. It consists of 45 sections on the basic elements of ground-water hydrology, arranged in order from the most basic aspects of the subject through a discussion of the methods used to determine the yield of aquifers to a discussion of common problems encountered in the operation of ground-water supplies.

Each section consists of a brief text and one or more drawings or maps that illustrate the main points covered in the text. Because the text is, in effect, an expanded discussion of the illustrations, most of the illustrations are not captioned. However, where more than one drawing is included in a section, each drawing is assigned a number, given in parentheses, and these numbers are inserted at places in the text where the reader should refer to the drawing.

In accordance with U.S. Geological Survey policy to encourage the use of metric units, these units are used in most sections. In the sections dealing with the analysis of aquifer (pumping) test data, equations are given in both consistent units and in the inconsistent inch-pound units still in relatively common use among ground-water hydrologists and well drillers. As an aid to those who are not familiar with metric units and with the conversion of ground-water hydraulic units from inch-pound units to metric units, conversion tables are given on the inside back cover.

Definitions of ground-water terms are given where the terms are first introduced. Because some of these terms will be new to many readers, abbreviated definitions are also given on the inside front cover for convenient reference by those who wish to review the definitions from time to time as they read the text. Finally, for those who need to review some of the simple mathematical operations that are used in ground-water hydrology, a section on numbers, equations, and conversions is included at the end of the text.

Ralph C. Heath

GROUND-WATER HYDROLOGY

The science of hydrology would be relatively simple if water were unable to penetrate below the earth's surface.

Harold E. Thomas

Ground-water hydrology is the subdivision of the science of hydrology that deals with the occurrence, movement, and quality of water beneath the Earth's surface. It is interdisciplinary in scope in that it involves the application of the physical, biological, and mathematical sciences. It is also a science whose successful application is of critical importance to the welfare of mankind. Because ground-water hydrology deals with the occurrence and movement of water in an almost infinitely complex subsurface environment, it is, in its most advanced state, one of the most complex of the sciences. On the other hand, many of its basic principles and methods can be understood readily by nonhydrologists and used by them in the solution of ground-water problems. The purpose of this report is to present these basic aspects of ground-water hydrology in a form that will encourage more widespread understanding and use.

The ground-water environment is hidden from view except in caves and mines, and the impression that we gain even from these are, to a large extent, misleading. From our observations on the land surface, we form an impression of a "solid" Earth. This impression is not altered very much when we enter a limestone cave and see water flowing in a channel that nature has cut into what appears to be solid rock. In fact, from our observations, both on the land surface and in caves, we are likely to conclude that ground water occurs only in underground rivers and "veins." We do not see the myriad openings that exist between the grains of sand and silt, between particles of clay, or even along the fractures in granite. Consequently, we do not sense the presence of the openings that, in total volume, far exceed the volume of all caves.

R. L. Nace of the U.S. Geological Survey has estimated that the total volume of subsurface openings (which are occupied mainly by water, gas, and petroleum) is on the order of 521,000 km³ (125,000 mi³) beneath the United States alone. If we visualize these openings as forming a continuous cave beneath the entire surface of the United States, its height would be about 57 m (186 ft). The openings, of course, are not equally distributed, the result being that our imaginary cave would range in height from about 3 m (10 ft) beneath the Piedmont Plateau along the eastern seaboard to about 2,500 m (8,200 ft) beneath the Mississippi Delta. The important point to be gained from this discussion is that the total volume of openings beneath the surface of the United States, and other land areas of the world, is very large.

Most subsurface openings contain water, and the importance of this water to mankind can be readily demonstrated by comparing its volume with the volumes of water in other parts of the hydrosphere.¹ Estimates of the volumes of water in the hydrosphere have been made by the Russian hydrologist M. I. L'vovich and are given in a book recently translated into English. Most water, including that in the oceans and in

the deeper subsurface openings, contains relatively large concentrations of dissolved minerals and is not readily usable for essential human needs. We will, therefore, concentrate in this discussion only on freshwater. The accompanying table contains L'vovich's estimates of the freshwater in the hydrosphere. Not surprisingly, the largest volume of freshwater occurs as ice in glaciers. On the other hand, many people impressed by the "solid" Earth are surprised to learn that about 14 percent of all freshwater is ground water and that, if only water is considered, 94 percent is ground water.

Ground-water hydrology, as noted earlier, deals not only with the occurrence of underground water but also with its movement. Contrary to our impressions of rapid movement as we observe the flow of streams in caves, the movement of most ground water is exceedingly slow. The truth of this observation becomes readily apparent from the table, which shows, in the last column, the rate of water exchange or the time required to replace the water now contained in the listed parts of the hydrosphere. It is especially important to note that the rate of exchange of 280 years for fresh ground water is about 1/9,000 the rate of exchange of water in rivers.

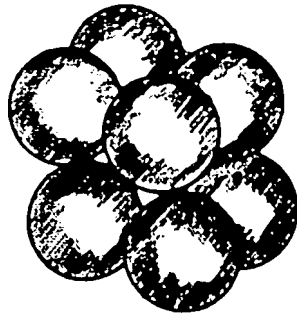
Subsurface openings large enough to yield water in a usable quantity to wells and springs underlie nearly every place on the land surface and thus make ground water one of the most widely available natural resources. When this fact and the fact that ground water also represents the largest reservoir of freshwater readily available to man are considered together, it is obvious that the value of ground water, in terms of both economics and human welfare, is incalculable. Consequently, its sound development, diligent conservation, and consistent protection from pollution are important concerns of everyone. These concerns can be translated into effective action only by increasing our knowledge of the basic aspects of ground-water hydrology.

FRESHWATER OF THE HYDROSPHERE AND ITS RATE OF EXCHANGE

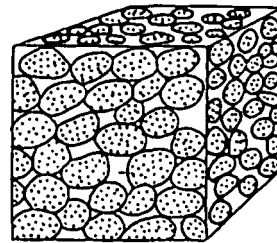
[Modified from L'vovich (1979), tables 2 and 10]

Parts of the hydrosphere	Volume of freshwater		Share in total volume of freshwater (percent)	Rate of water exchange (yr)
	km ³	mi ³		
Ice sheets and glaciers -----	24,000,000	5,800,000	84.945	8,000
Ground water ---	4,000,000	960,000	14.158	280
Lakes and reservoirs ----	155,000	37,000	.549	7
Soil moisture ---	83,000	20,000	.294	1
Vapors in the atmosphere --	14,000	3,400	.049	.027
River water ----	1,200	300	.004	.031
Total -----	28,253,200	6,820,700	100.000	

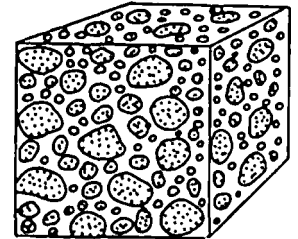
¹The hydrosphere is the term used to refer to the waters of the Earth and, in its broadest usage, includes all water, water vapor, and ice regardless of whether they occur beneath, on, or above the Earth's surface.



POROUS MATERIAL

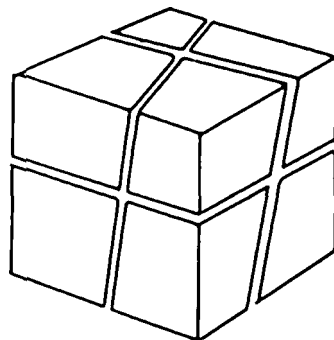


WELL-SORTED SAND



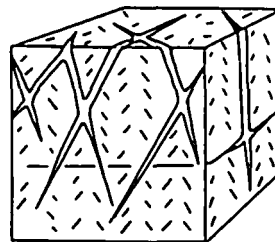
POORLY-SORTED SAND

PRIMARY OPENINGS

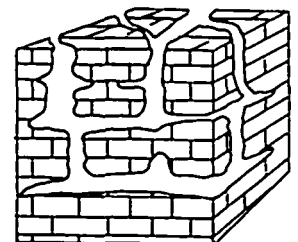


FRACTURED ROCK

(1)



FRACTURES IN
GRANITE



CAVERNS IN
LIMESTONE

SECONDARY OPENINGS

(2)

Most of the rocks near the Earth's surface are composed of both solids and voids, as sketch 1 shows. The solid part is, of course, much more obvious than the voids, but, without the voids, there would be no water to supply wells and springs.

Water-bearing rocks consist either of unconsolidated (soil-like) deposits or consolidated rocks. The Earth's surface in most places is formed by soil and by unconsolidated deposits that range in thickness from a few centimeters near outcrops of consolidated rocks to more than 12,000 m beneath the delta of the Mississippi River. The unconsolidated deposits are underlain everywhere by consolidated rocks.

Most *unconsolidated deposits* consist of material derived from the disintegration of consolidated rocks. The material consists, in different types of unconsolidated deposits, of particles of rocks or minerals ranging in size from fractions of a millimeter (clay size) to several meters (boulders). Unconsolidated deposits important in ground-water hydrology include,

in order of increasing grain size, clay, silt, sand, and gravel. An important group of unconsolidated deposits also includes fragments of shells of marine organisms.

Consolidated rocks consist of mineral particles of different sizes and shapes that have been welded by heat and pressure or by chemical reactions into a solid mass. Such rocks are commonly referred to in ground-water reports as *bedrock*. They include sedimentary rocks that were originally unconsolidated and igneous rocks formed from a molten state. Consolidated sedimentary rocks important in ground-water hydrology include limestone, dolomite, shale, siltstone, sandstone, and conglomerate. Igneous rocks include granite and basalt.

There are different kinds of voids in rocks, and it is sometimes useful to be aware of them. If the voids were formed at the same time as the rock, they are referred to as *primary openings* (2). The pores in sand and gravel and in other unconsolidated deposits are primary openings. The lava tubes and other openings in basalt are also primary openings.

If the voids were formed after the rock was formed, they are referred to as *secondary openings* (2). The fractures in granite and in consolidated sedimentary rocks are secondary openings. Voids in limestone, which are formed as ground water slowly dissolves the rock, are an especially important type of secondary opening.

It is useful to introduce the topic of rocks and water by dealing with unconsolidated deposits on one hand and with

consolidated rocks on the other. It is important to note, however, that many sedimentary rocks that serve as sources of ground water fall between these extremes in a group of *semi-consolidated rocks*. These are rocks in which openings include both pores and fractures—in other words, both primary and secondary openings. Many limestones and sandstones that are important sources of ground water are semiconsolidated.

UNDERGROUND WATER

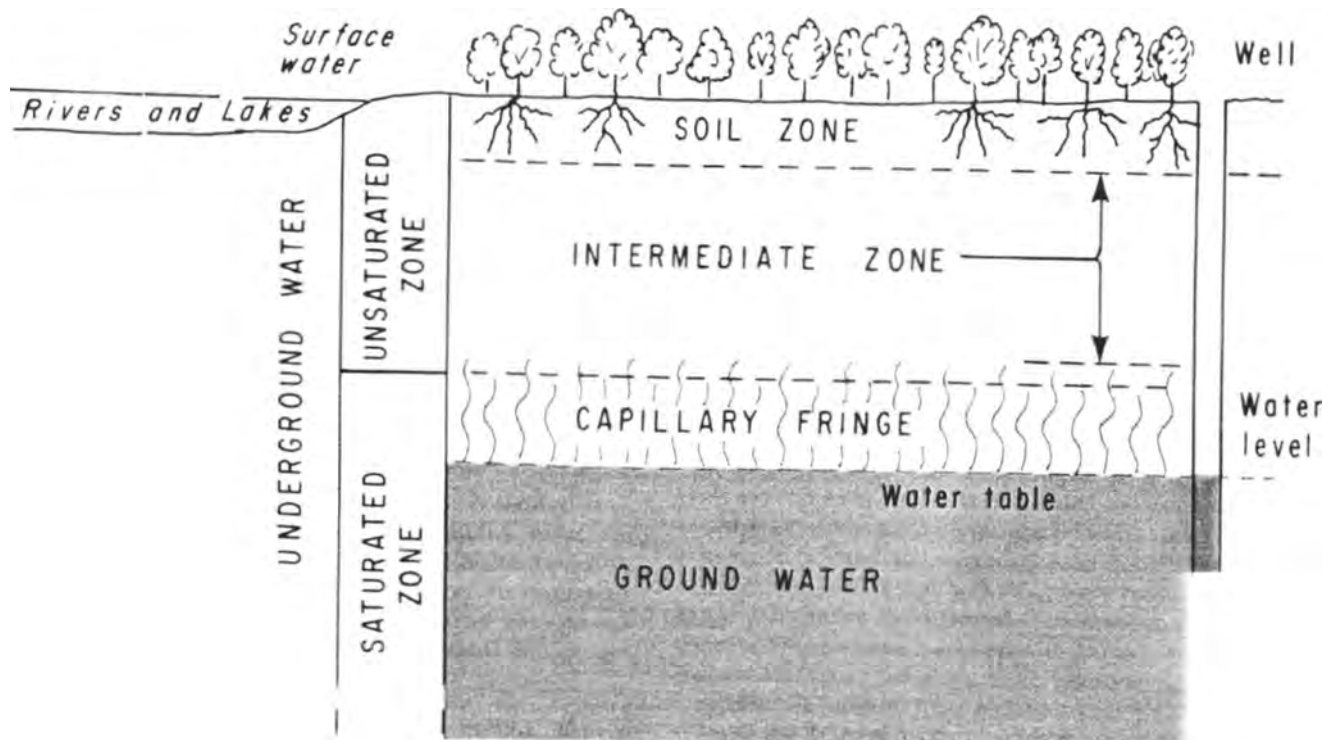
All water beneath the land surface is referred to as *underground water* (or *subsurface water*). The equivalent term for water on the land surface is *surface water*. Underground water occurs in two different zones. One zone, which occurs immediately below the land surface in most areas, contains both water and air and is referred to as the *unsaturated zone*. The unsaturated zone is almost invariably underlain by a zone in which all interconnected openings are full of water. This zone is referred to as the *saturated zone*.

Water in the saturated zone is the only underground water that is available to supply wells and springs and is the only water to which the name *ground water* is correctly applied. Recharge of the saturated zone occurs by percolation of water from the land surface through the unsaturated zone. The unsaturated zone is, therefore, of great importance to ground-water hydrology. This zone may be divided usefully into three parts: the *soil zone*, the *intermediate zone*, and the upper part of the *capillary fringe*.

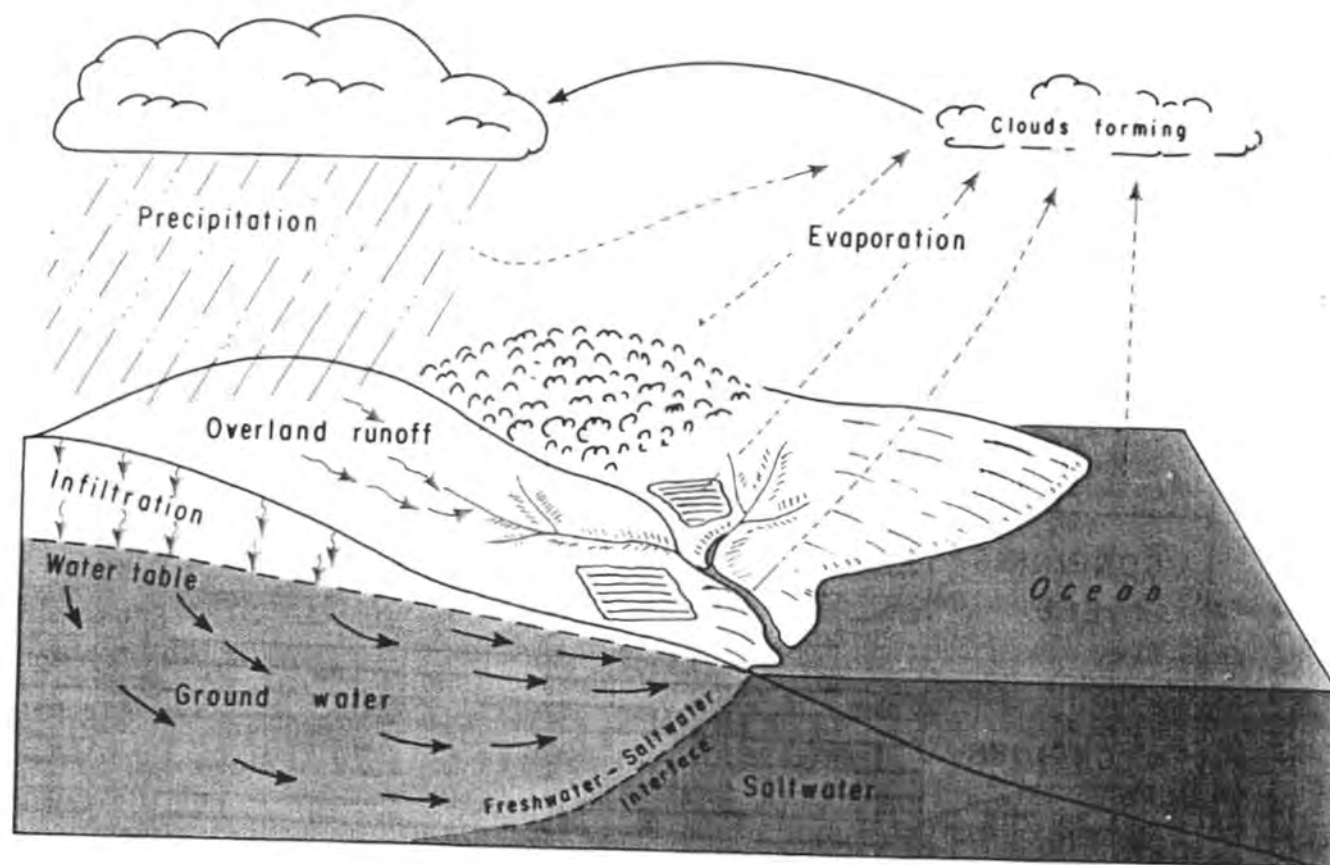
The soil zone extends from the land surface to a maximum depth of a meter or two and is the zone that supports plant growth. It is crisscrossed by living roots, by voids left by

decayed roots of earlier vegetation, and by animal and worm burrows. The porosity and permeability of this zone tend to be higher than those of the underlying material. The soil zone is underlain by the *intermediate zone*, which differs in thickness from place to place depending on the thickness of the soil zone and the depth to the capillary fringe.

The lowest part of the unsaturated zone is occupied by the *capillary fringe*, the subzone between the unsaturated and saturated zones. The capillary fringe results from the attraction between water and rocks. As a result of this attraction, water clings as a film on the surface of rock particles and rises in small-diameter pores against the pull of gravity. Water in the capillary fringe and in the overlying part of the unsaturated zone is under a negative hydraulic pressure—that is, it is under a pressure less than the atmospheric (barometric) pressure. The *water table* is the level in the saturated zone at which the hydraulic pressure is equal to atmospheric pressure and is represented by the water level in unused wells. Below the water table, the hydraulic pressure increases with increasing depth.



HYDROLOGIC CYCLE



The term *hydrologic cycle* refers to the constant movement of water above, on, and below the Earth's surface. The concept of the hydrologic cycle is central to an understanding of the occurrence of water and the development and management of water supplies.

Although the hydrologic cycle has neither a beginning nor an end, it is convenient to discuss its principal features by starting with evaporation from vegetation, from exposed moist surfaces including the land surface, and from the ocean. This moisture forms clouds, which return the water to the land surface or oceans in the form of precipitation.

Precipitation occurs in several forms, including rain, snow, and hail, but only rain is considered in this discussion. The first rain wets vegetation and other surfaces and then begins to infiltrate into the ground. *Infiltration* rates vary widely, depending on land use, the character and moisture content of the soil, and the intensity and duration of precipitation, from possibly as much as 25 mm/hr in mature forests on sandy soils to a few millimeters per hour in clayey and silty soils to zero in paved areas. When and if the rate of precipitation exceeds the rate of infiltration, *overland flow* occurs.

The first infiltration replaces soil moisture, and, thereafter, the excess percolates slowly across the intermediate zone to the zone of saturation. Water in the zone of saturation moves

downward and laterally to sites of ground-water discharge such as springs on hillsides or seeps in the bottoms of streams and lakes or beneath the ocean.

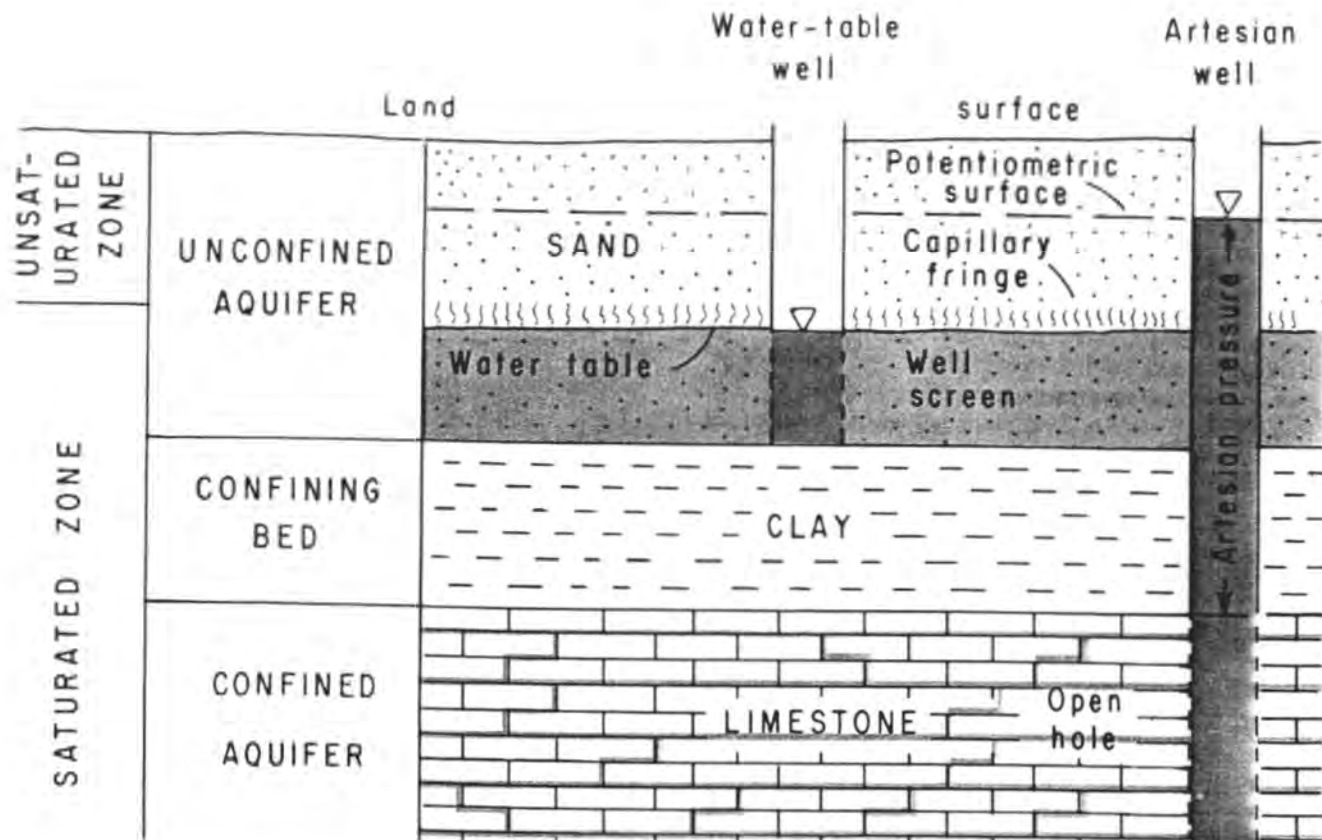
Water reaching streams, both by overland flow and from ground-water discharge, moves to the sea, where it is again evaporated to perpetuate the cycle.

Movement is, of course, the key element in the concept of the hydrologic cycle. Some "typical" rates of movement are shown in the following table, along with the distribution of the Earth's water supply.

RATE OF MOVEMENT AND DISTRIBUTION OF WATER
[Adapted from L'vovich (1979), table 1]

Location	Rate of movement	Distribution of Earth's water supply (percent)
Atmosphere —	100's of kilometers per day	0.001
Water on land surface —	10's of kilometers per day	.019
Water below the land surface —	Meters per year	4.12
Ice caps and glaciers —	Meters per day	1.65
Oceans —	—	93.96

AQUIFERS AND CONFINING BEDS



From the standpoint of ground-water occurrence, all rocks that underlie the Earth's surface can be classified either as aquifers or as confining beds. An *aquifer* is a rock unit that will yield water in a usable quantity to a well or spring. (In geologic usage, "rock" includes unconsolidated sediments.) A *confining bed* is a rock unit having very low hydraulic conductivity that restricts the movement of ground water either into or out of adjacent aquifers.

Ground water occurs in aquifers under two different conditions. Where water only partly fills an aquifer, the upper surface of the saturated zone is free to rise and decline. The water in such aquifers is said to be *unconfined*, and the aquifers are referred to as *unconfined aquifers*. Unconfined aquifers are also widely referred to as *water-table aquifers*.

Where water completely fills an aquifer that is overlain by a confining bed, the water in the aquifer is said to be *confined*. Such aquifers are referred to as *confined aquifers* or as *artesian aquifers*.

Wells open to unconfined aquifers are referred to as *water-table wells*. The water level in these wells indicates the position of the water table in the surrounding aquifer.

Wells drilled into confined aquifers are referred to as *artesian wells*. The water level in artesian wells stands at some height above the top of the aquifer but not necessarily above the land surface. If the water level in an artesian well stands above the land surface, the well is a *flowing artesian well*. The water level in tightly cased wells open to a confined aquifer stands at the level of the *potentiometric surface* of the aquifer.

POROSITY

The ratio of openings (voids) to the total volume of a soil or rock is referred to as its porosity. Porosity is expressed either as a decimal fraction or as a percentage. Thus,

$$n = \frac{V_t - V_s}{V_t} = \frac{V_v}{V_t}$$

where n is porosity as a decimal fraction, V_t is the total volume of a soil or rock sample, V_s is the volume of solids in the sample, and V_v is the volume of openings (voids).

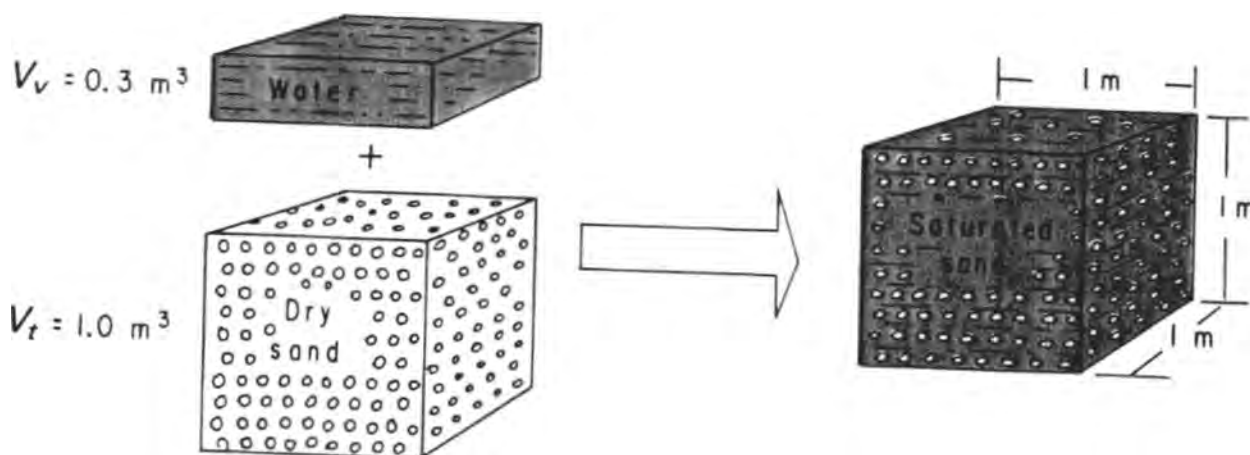
If we multiply the porosity determined with the equation by 100, the result is porosity expressed as a percentage.

Soils are among the most porous of natural materials because soil particles tend to form loose clumps and because of the presence of root holes and animal burrows. Porosity of unconsolidated deposits depends on the range in grain size (sorting) and on the shape of the rock particles but not on their size. Fine-grained materials tend to be better sorted and, thus, tend to have the largest porosities.

SELECTED VALUES OF POROSITY

[Values in percent by volume]

Material	Primary openings	Secondary openings
Equal-size spheres (marbles):		
Loosest packing	48	—
Tightest packing	26	—
Soil	55	—
Clay	50	—
Sand	25	—
Gravel	20	—
Limestone	10	10
Sandstone (semiconsolidated)	10	1
Granite	—	1
Basalt (young)	10	1



$$\text{Porosity } (n) = \frac{\text{Volume of voids } (V_v)}{\text{Total volume } (V_t)} = \frac{0.3 \text{ m}^3}{1.0 \text{ m}^3} = 0.30$$

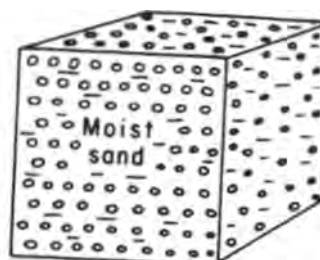
SPECIFIC YIELD AND SPECIFIC RETENTION

Porosity is important in ground-water hydrology because it tells us the maximum amount of water that a rock can contain when it is saturated. However, it is equally important to know that only a part of this water is available to supply a well or a spring.

Hydrologists divide water in storage in the ground into the

part that will drain under the influence of gravity (called *specific yield*) (1) and the part that is retained as a film on rock surfaces and in very small openings (called *specific retention*) (2). The physical forces that control specific retention are the same forces involved in the thickness and moisture content of the capillary fringe.

$$S_r = 0.1 \text{ m}^3$$

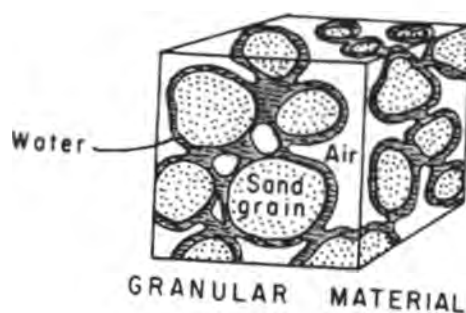


$$S_y = 0.2 \text{ m}^3$$

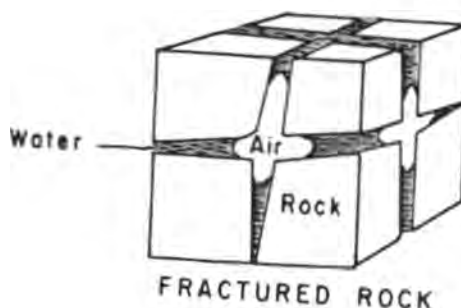


$$n = S_y + S_r = \frac{0.2 \text{ m}^3}{1 \text{ m}^3} + \frac{0.1 \text{ m}^3}{1 \text{ m}^3} = 0.30$$

(1)



Water retained as a film on rock surfaces and in capillary-size openings after gravity drainage.



(2)

Specific yield tells how much water is available for man's use, and specific retention tells how much water remains in the rock after it is drained by gravity. Thus,

$$n = S_y + S_r$$

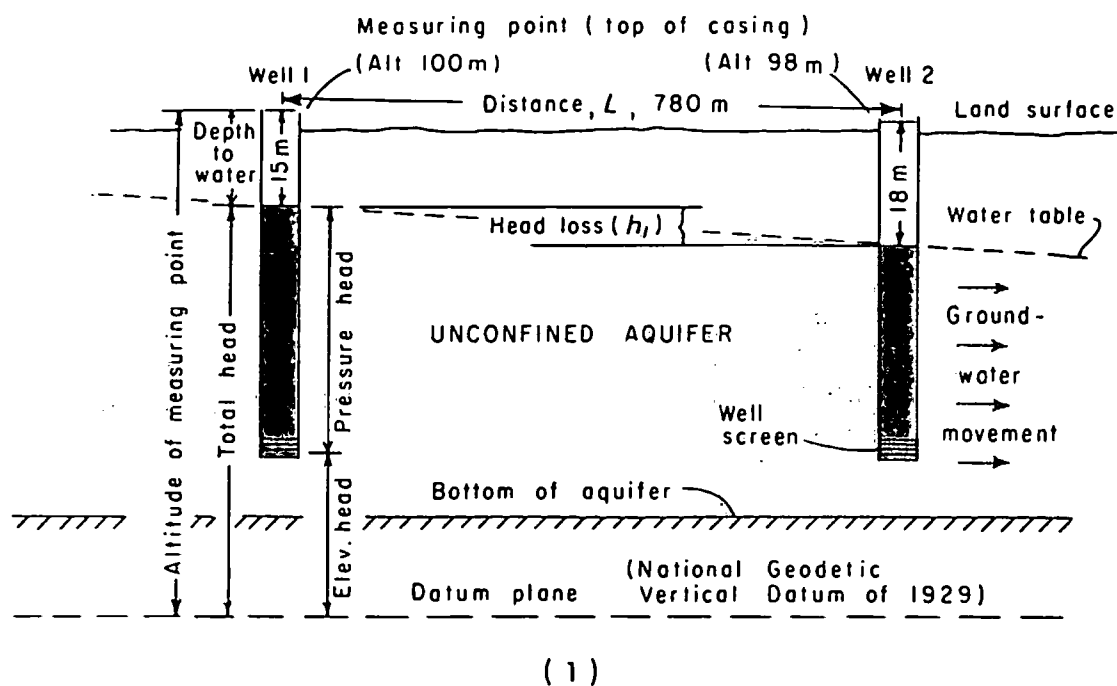
$$S_y = \frac{V_d}{V_t} \quad S_r = \frac{V_r}{V_t}$$

where n is porosity, S_y is specific yield, S_r is specific retention, V_d is the volume of water that drains from a total volume of V_t , V_r is the volume of water retained in a total volume of V_t , and V_t is total volume of a soil or rock sample.

SELECTED VALUES OF POROSITY, SPECIFIC YIELD, AND SPECIFIC RETENTION (Values in percent by volume)

Material	Porosity	Specific yield	Specific retention
Soil -----	55	40	15
Clay -----	50	2	48
Sand -----	25	22	3
Gravel -----	20	19	1
Limestone -----	20	18	2
Sandstone (semiconsolidated) -----	11	6	5
Granite -----	.1	.09	.01
Basalt (young) -----	11	8	3

HEADS AND GRADIENTS



The depth to the water table has an important effect on use of the land surface and on the development of water supplies from unconfined aquifers (1). Where the water table is at a shallow depth, the land may become "waterlogged" during wet weather and unsuitable for residential and many other uses. Where the water table is at great depth, the cost of constructing wells and pumping water for domestic needs may be prohibitively expensive.

The direction of the slope of the water table is also important because it indicates the direction of ground-water movement (1). The position and the slope of the water table (or of the potentiometric surface of a confined aquifer) is determined by measuring the position of the water level in wells from a fixed point (a measuring point) (1). (See "Measurements of Water Levels and Pumping Rates.") To utilize these measurements to determine the slope of the water table, the position of the water table at each well must be determined relative to a datum plane that is common to all the wells. The datum plane most widely used is the National Geodetic Vertical Datum of 1929 (also commonly referred to as "sea level") (1).

If the depth to water in a nonflowing well is subtracted from the altitude of the measuring point, the result is the total head at the well. Total head, as defined in fluid mechanics, is composed of elevation head, pressure head, and velocity head. Because ground water moves relatively slowly, velocity head can be ignored. Therefore, the total head at an observation well involves only two components: elevation head and pressure head (1). Ground water moves in the direction of decreasing total head, which may or may not be in the direction of decreasing pressure head.

The equation for total head (h_t) is

$$h_t = z + h_p$$

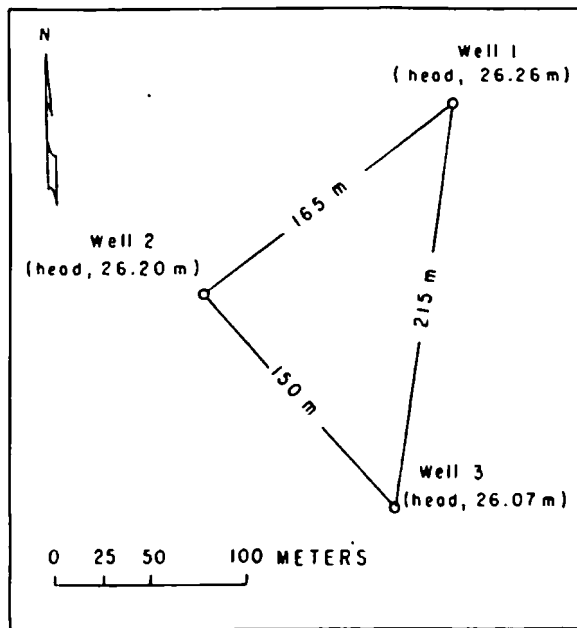
where z is elevation head and is the distance from the datum plane to the point where the pressure head h_p is determined.

All other factors being constant, the rate of ground-water movement depends on the hydraulic gradient. The hydraulic gradient is the change in head per unit of distance in a given direction. If the direction is not specified, it is understood to be in the direction in which the maximum rate of decrease in head occurs.

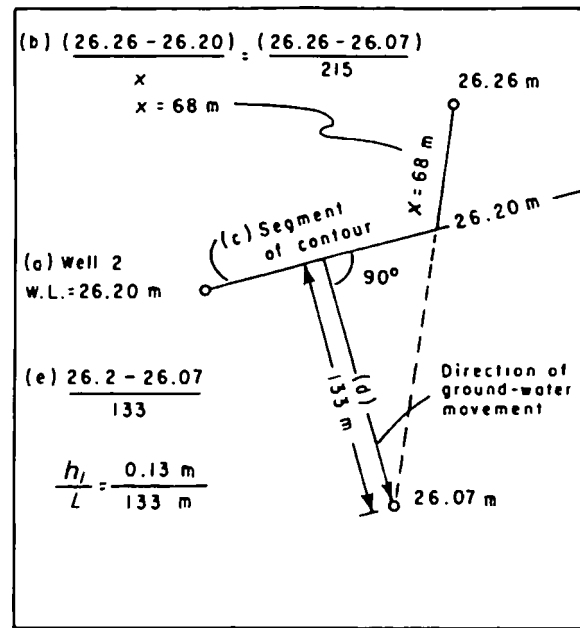
If the movement of ground water is assumed to be in the plane of sketch 1—in other words, if it moves from well 1 to well 2—the hydraulic gradient can be calculated from the information given on the drawing. The hydraulic gradient is h_L/L , where h_L is the head loss between wells 1 and 2 and L is the horizontal distance between them, or

$$\frac{h_L}{L} = \frac{(100 \text{ m} - 15 \text{ m}) - (98 \text{ m} - 18 \text{ m})}{780 \text{ m}} = \frac{85 \text{ m} - 80 \text{ m}}{780 \text{ m}} = \frac{5 \text{ m}}{780 \text{ m}}$$

When the hydraulic gradient is expressed in consistent units, as it is in the above example in which both the numerator and the denominator are in meters, any other consistent units of length can be substituted without changing the value of the gradient. Thus, a gradient of 5 ft/780 ft is the same as a gradient of 5 m/780 m. It is also relatively common to express hydraulic gradients in inconsistent units such as meters per



(2)



(3)

kilometer or feet per mile. A gradient of 5 m/780 m can be converted to meters per kilometer as follows:

$$\left(\frac{5 \text{ m}}{780 \text{ m}} \right) \times \left(\frac{1,000 \text{ m}}{\text{km}} \right) = 6.4 \text{ m km}^{-1}$$

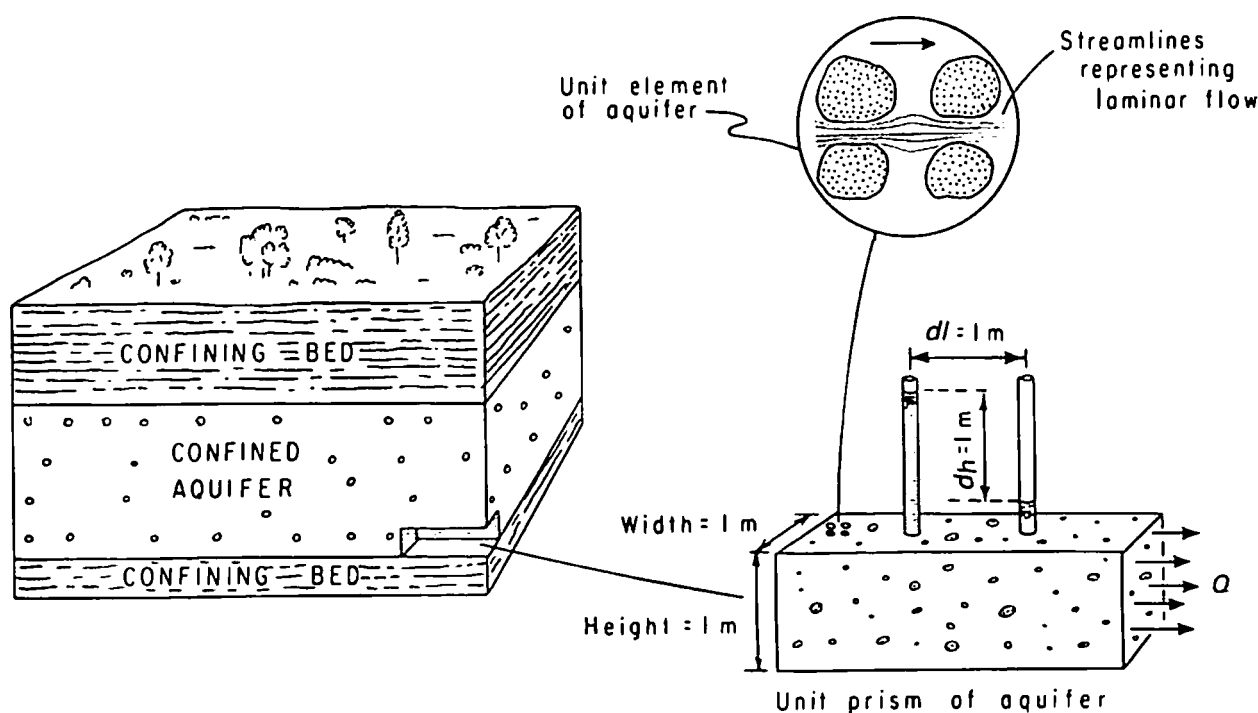
Both the direction of ground-water movement and the hydraulic gradient can be determined if the following data are available for three wells located in any triangular arrangement such as that shown on sketch 2:

1. The relative geographic position of the wells.
2. The distance between the wells.
3. The total head at each well.

Steps in the solution are outlined below and illustrated in sketch 3:

- a. Identify the well that has the intermediate water level (that is, neither the highest head nor the lowest head).
- b. Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.
- c. Draw a straight line between the intermediate well and the point identified in step b as being between the well having the highest head and that having the lowest head. This line represents a segment of the water-level contour along which the total head is the same as that in the intermediate well.
- d. Draw a line perpendicular to the water-level contour and through either the well with the highest head or the well with the lowest head. This line parallels the direction of ground-water movement.
- e. Divide the difference between the head of the well and that of the contour by the distance between the well and the contour. The answer is the hydraulic gradient.

HYDRAULIC CONDUCTIVITY



(1)

Aquifers transmit water from recharge areas to discharge areas and thus function as porous conduits (or pipelines filled with sand or other water-bearing material). The factors controlling ground-water movement were first expressed in the form of an equation by Henry Darcy, a French engineer, in 1856. Darcy's law is

$$Q = KA \left(\frac{dh}{dl} \right) \quad (1)$$

where Q is the quantity of water per unit of time; K is the hydraulic conductivity and depends on the size and arrangement of the water-transmitting openings (pores and fractures) and on the dynamic characteristics of the fluid (water) such as kinematic viscosity, density, and the strength of the gravitational field; A is the cross-sectional area, at a right angle to the flow direction, through which the flow occurs; and dh/dl is the hydraulic gradient.¹

Because the quantity of water (Q) is directly proportional to the hydraulic gradient (dh/dl), we say that ground-water flow is *laminar*—that is, water particles tend to follow discrete streamlines and not to mix with particles in adjacent streamlines (1). (See "Ground-Water Flow Nets.")

¹Where hydraulic gradient is discussed as an independent entity, as it is in "Heads and Gradients," it is shown symbolically as h_l/L and is referred to as head loss per unit of distance. Where hydraulic gradient appears as one of the factors in an equation, as it does in equation 1, it is shown symbolically as dh/dl to be consistent with other ground-water literature. The gradient dh/dl indicates that the unit distance is reduced to as small a value as one can imagine, in accordance with the concepts of differential calculus.

If we rearrange equation 1 to solve for K , we obtain

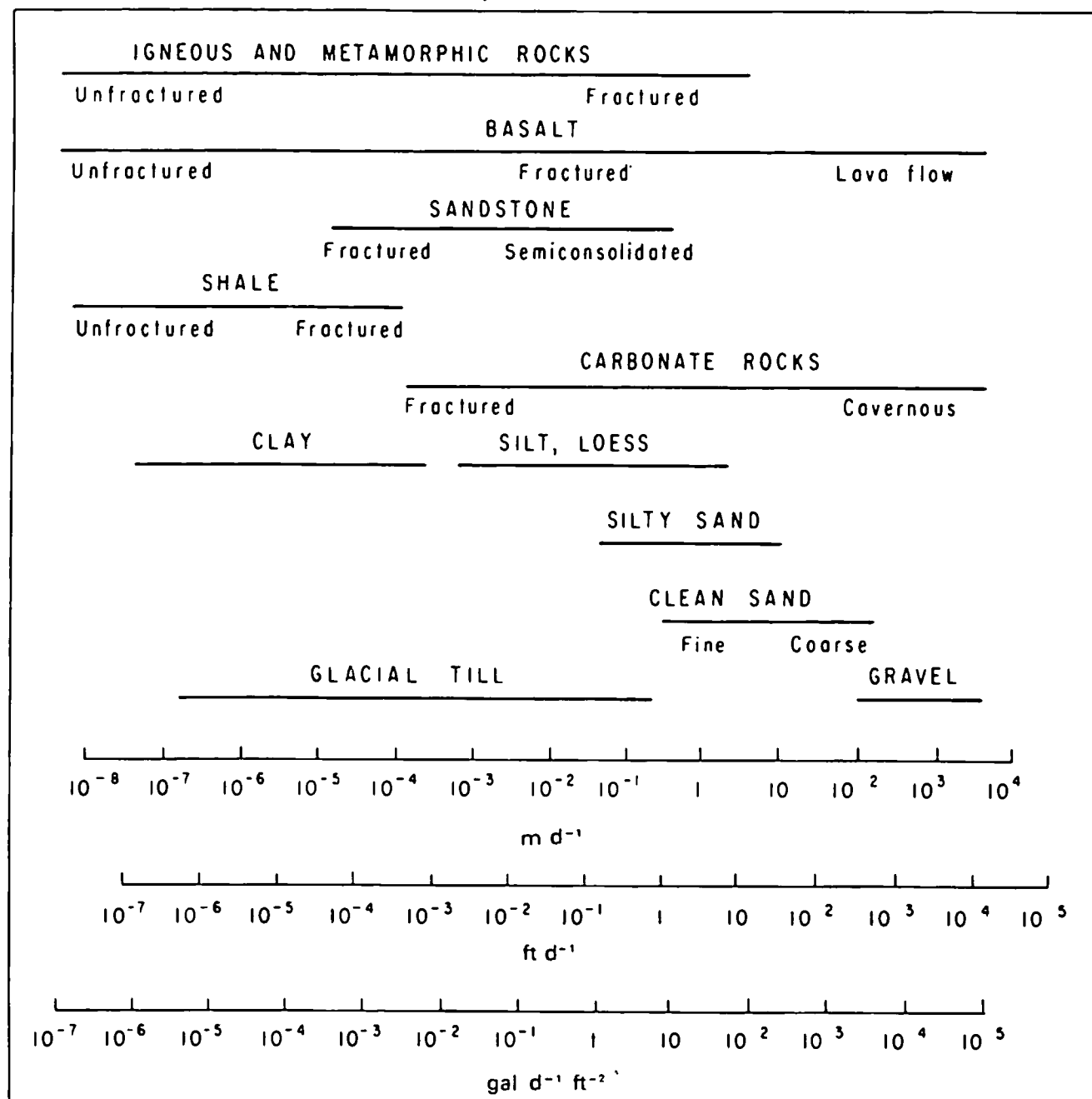
$$K = \frac{Qdl}{A dh} = \frac{(m^3 d^{-1})(m)}{(m^2)(m)} = \frac{m}{d} \quad (2)$$

Thus, the units of hydraulic conductivity are those of velocity (or distance divided by time). It is important to note from equation 2, however, that the factors involved in the definition of hydraulic conductivity include the volume of water (Q) that will move in a unit of time (commonly, a day) under a unit hydraulic gradient (such as a meter per meter) through a unit area (such as a square meter). These factors are illustrated in sketch 1. Expressing hydraulic conductivity in terms of a unit gradient, rather than of an actual gradient at some place in an aquifer, permits ready comparison of values of hydraulic conductivity for different rocks.

Hydraulic conductivity replaces the term "field coefficient of permeability" and should be used in referring to the water-transmitting characteristic of material in quantitative terms. It is still common practice to refer in qualitative terms to "permeable" and "impermeable" material.

The hydraulic conductivity of rocks ranges through 12 orders of magnitude (2). There are few physical parameters whose values range so widely. Hydraulic conductivity is not only different in different types of rocks but may also be different from place to place in the same rock. If the hydraulic conductivity is essentially the same in any area, the aquifer in

Hydraulic Conductivity of Selected Rocks



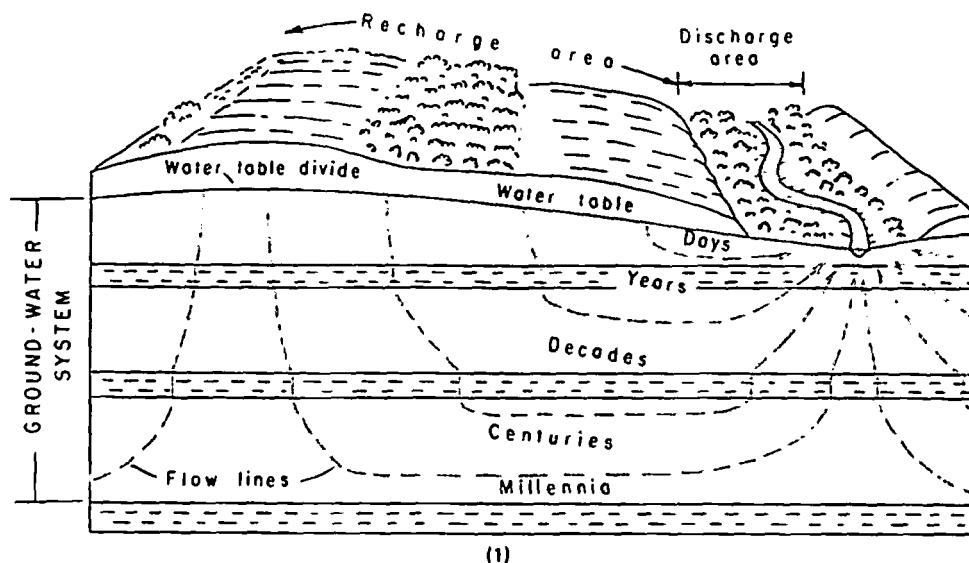
(2)

that area is said to be *homogeneous*. If, on the other hand, the hydraulic conductivity differs from one part of the area to another, the aquifer is said to be *heterogeneous*.

Hydraulic conductivity may also be different in different directions at any place in an aquifer. If the hydraulic conductivity is essentially the same in all directions, the aquifer is said to be *isotropic*. If it is different in different directions, the aquifer is said to be *anisotropic*.

Although it is convenient in many mathematical analyses of ground-water flow to assume that aquifers are both homogeneous and isotropic, such aquifers are rare, if they exist at all. The condition most commonly encountered is for hydraulic conductivity in most rocks and especially in unconsolidated deposits and in flat-lying consolidated sedimentary rocks to be larger in the horizontal direction than it is in the vertical direction.

FUNCTIONS OF GROUND-WATER SYSTEMS



The aquifers and confining beds that underlie any area comprise the *ground-water system* of the area (1). Hydraulically, this system serves two functions: it stores water to the extent of its porosity, and it transmits water from recharge areas to discharge areas. Thus, a ground-water system serves as both a reservoir and a conduit. With the exception of cavernous limestones, lava flows, and coarse gravels, ground-water systems are more effective as reservoirs than as conduits.

Water enters ground-water systems in *recharge areas* and moves through them, as dictated by hydraulic gradients and hydraulic conductivities, to *discharge areas* (1).

The identification of recharge areas is becoming increasingly important because of the expanding use of the land surface for waste disposal. In the humid part of the country, recharge occurs in all interstream areas—that is, in all areas except along streams and their adjoining flood plains (1). The streams and flood plains are, under most conditions, discharge areas.

In the drier part (western half) of the conterminous United States, recharge conditions are more complex. Most recharge occurs in the mountain ranges, on alluvial fans that border the mountain ranges, and along the channels of major streams where they are underlain by thick and permeable alluvial deposits.

Recharge rates are generally expressed in terms of volume (such as cubic meters or gallons) per unit of time (such as a day or a year) per unit of area (such as a square kilometer, a square mile, or an acre). When these units are reduced to their simplest forms, the result is recharge expressed as a depth of water on the land surface per unit of time. Recharge varies from year to year, depending on the amount of precipitation, its seasonal distribution, air temperature, land use, and other factors. Relative to land use, recharge rates in forests are much higher than those in cities.

Annual recharge rates range, in different parts of the coun-

try, from essentially zero in desert areas to about 600 mm yr^{-1} ($1,600 \text{ m}^3 \text{ km}^{-2} \text{ d}^{-1}$ or $1.1 \times 10^6 \text{ gal mi}^{-2} \text{ d}^{-1}$) in the rural areas on Long Island and in other rural areas in the East that are underlain by very permeable soils.

The rate of movement of ground water from recharge areas to discharge areas depends on the hydraulic conductivities of the aquifers and confining beds, if water moves downward into other aquifers, and on the hydraulic gradients. (See "Ground-Water Velocity.") A convenient way of showing the rate is in terms of the time required for ground water to move from different parts of a recharge area to the nearest discharge area. The time ranges from a few days in the zone adjacent to the discharge area to thousands of years (millennia) for water that moves from the central part of some recharge areas through the deeper parts of the ground-water system (1).

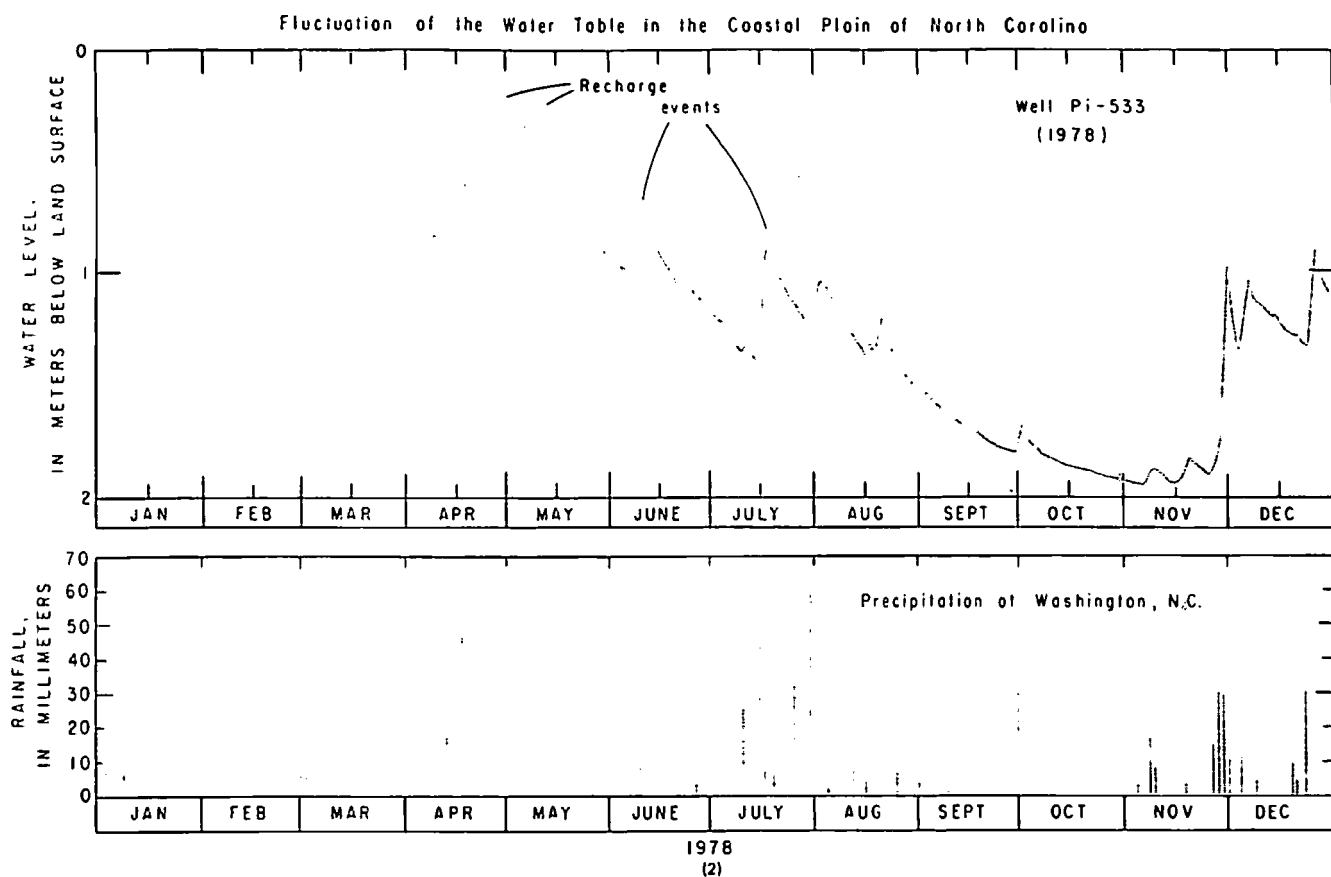
Natural discharge from ground-water systems includes not only the flow of springs and the seepage of water into stream channels or wetlands but also evaporation from the upper part of the capillary fringe, where it occurs within a meter or so of the land surface. Large amounts of water are also withdrawn from the capillary fringe and the zone of saturation by plants during the growing season. Thus, discharge areas include not only the channels of perennial streams but also the adjoining flood plains and other low-lying areas.

One of the most significant differences between recharge areas and discharge areas is that the areal extent of discharge areas is invariably much smaller than that of recharge areas. This size difference shows, as we would expect, that discharge areas are more "efficient" than recharge areas. Recharge involves unsaturated movement of water in the vertical direction; in other words, movement is in the direction in which the hydraulic conductivity is generally the lowest. Discharge, on the other hand, involves saturated movement, much of it in the horizontal direction—that is, in the direction of the largest hydraulic conductivity.

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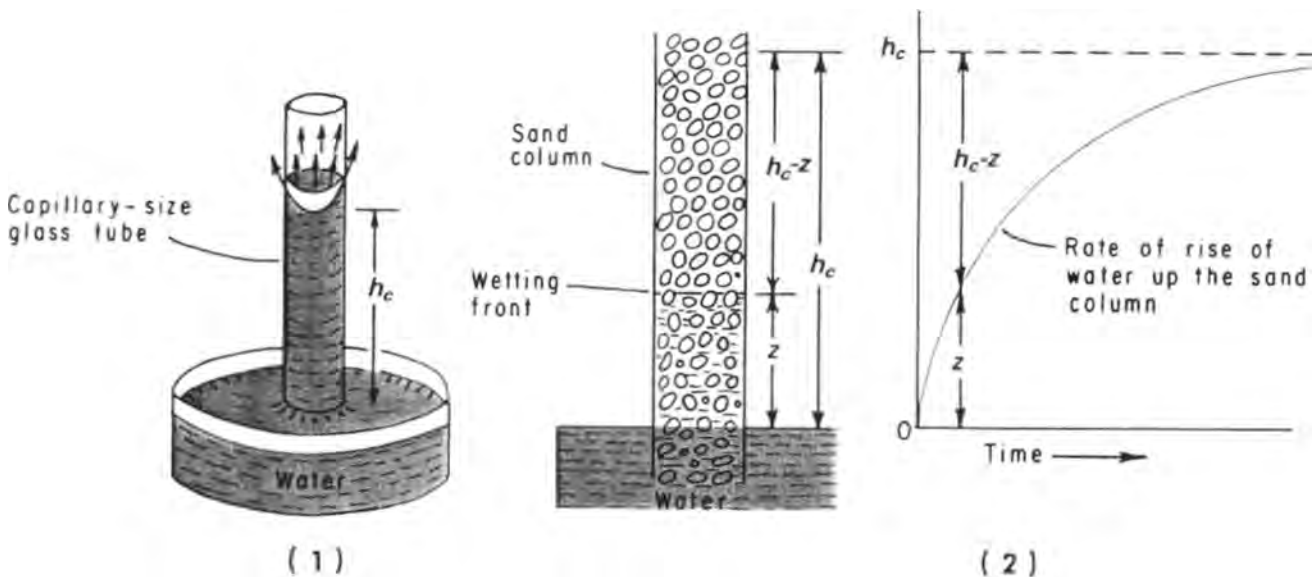
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Another important aspect of recharge and discharge involves timing. Recharge occurs during and immediately following periods of precipitation and thus is intermittent (2). Discharge, on the other hand, is a continuous process as long as ground-water heads are above the level at which discharge occurs. However, between periods of recharge, ground-water heads decline, and the rate of discharge also declines. Most recharge of ground-water systems occurs during late fall,

winter, and early spring, when plants are dormant and evaporation rates are small. These aspects of recharge and discharge are apparent from graphs showing the fluctuation of the water level in observation wells, such as the one shown in sketch 2. The occasional lack of correlation, especially in the summer, between the precipitation and the rise in water level is due partly to the distance of 20 km between the weather station and the well.

CAPILLARITY AND UNSATURATED FLOW



Most recharge of ground-water systems occurs during the percolation of water across the unsaturated zone. The movement of water in the unsaturated zone is controlled by both gravitational and capillary forces.

Capillarity results from two forces: the mutual attraction (cohesion) between water molecules and the molecular attraction (adhesion) between water and different solid materials. As a consequence of these forces, water will rise in small-diameter glass tubes to a height h_c above the water level in a large container (1).

Most pores in granular materials are of capillary size, and, as a result, water is pulled upward into a capillary fringe above the water table in the same manner that water would be pulled up into a column of sand whose lower end is immersed in water (2).

APPROXIMATE HEIGHT OF CAPILLARY RISE (h_c) IN GRANULAR MATERIALS

Material	Rise (mm)
Sand:	
Coarse	125
Medium	250
Fine	400
Silt	1,000

Steady-state flow of water in the unsaturated zone can be determined from a modified form of Darcy's law. Steady state in this context refers to a condition in which the moisture content remains constant, as it would, for example, beneath a waste-disposal pond whose bottom is separated from the water table by an unsaturated zone.

Steady-state unsaturated flow (Q) is proportional to the effective hydraulic conductivity (K_e), the cross-sectional area (A) through which the flow occurs, and gradients due to both capillary forces and gravitational forces. Thus,

$$Q = K_e A \left(\frac{h_c - z}{z} \right) \pm \left(\frac{dh}{dl} \right) \quad (1)$$

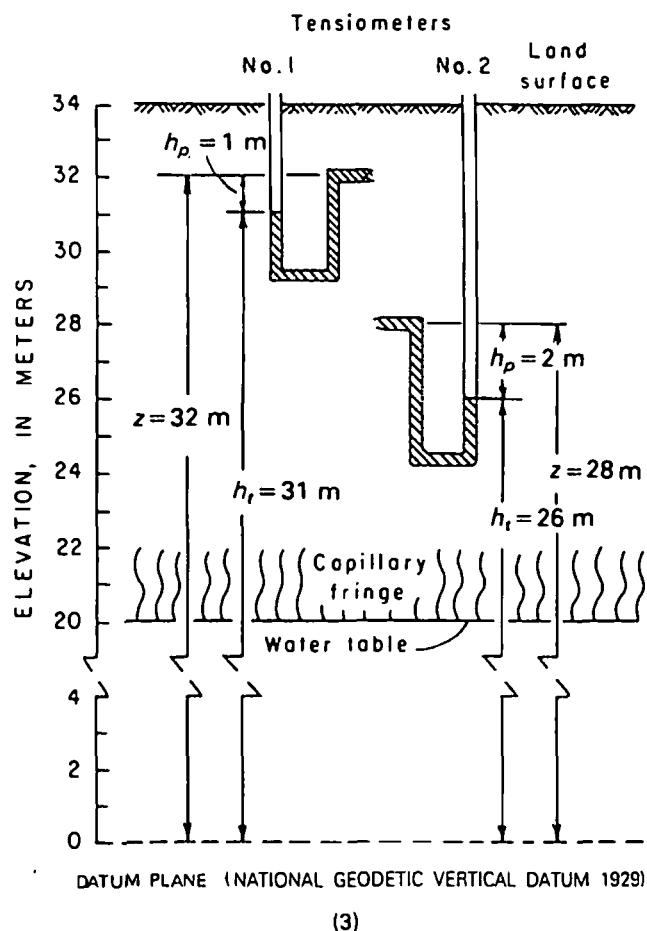
where Q is the quantity of water, K_e is the hydraulic conductivity under the degree of saturation existing in the unsaturated zone, $(h_c - z)/z$ is the gradient due to capillary (surface tension) forces, and dh/dl is the gradient due to gravity.

The plus or minus sign is related to the direction of movement—plus for downward and minus for upward. For movement in a vertical direction, either up or down, the gradient due to gravity is $1/l$, or 1. For lateral (horizontal) movement in the unsaturated zone, the term for the gravitational gradient can be eliminated.

The capillary gradient at any time depends on the length of the water column (z) supported by capillarity in relation to the maximum possible height of capillary rise (h_c) (2). For example, if the lower end of a sand column is suddenly submerged in water, the capillary gradient is at a maximum, and the rate of rise of water is fastest. As the wetting front advances up the column, the capillary gradient declines, and the rate of rise decreases (2).

The capillary gradient can be determined from tensiometer measurements of hydraulic pressures. To determine the gradient, it is necessary to measure the negative pressures (h_p) at two levels in the unsaturated zone, as sketch 3 shows. The equation for total head (h_t) is

$$h_t = z + h_p \quad (2)$$



where z is the elevation of a tensiometer. Substituting values in this equation for tensiometer no. 1, we obtain

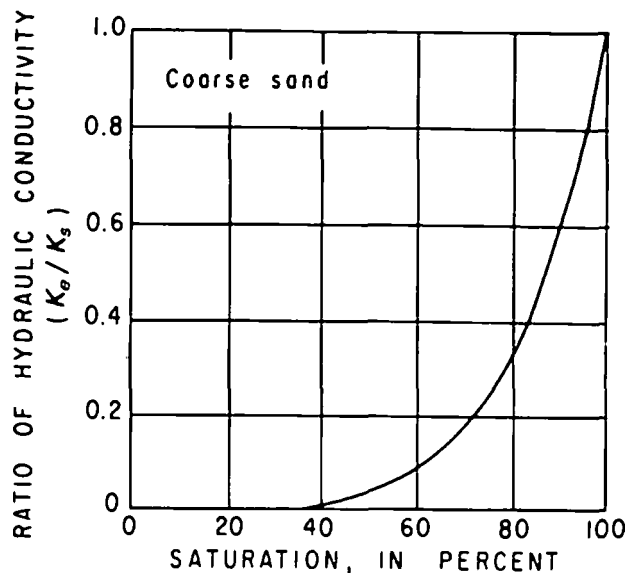
$$h_t = 32 + (-1) = 32 - 1 = 31 \text{ m}$$

The total head at tensiometer no. 2 is 26 m. The vertical distance between the tensiometers is 32 m minus 28 m, or 4 m. Because the combined gravitational and capillary hydraulic

gradient equals the head loss divided by the distance between tensiometers, the gradient is

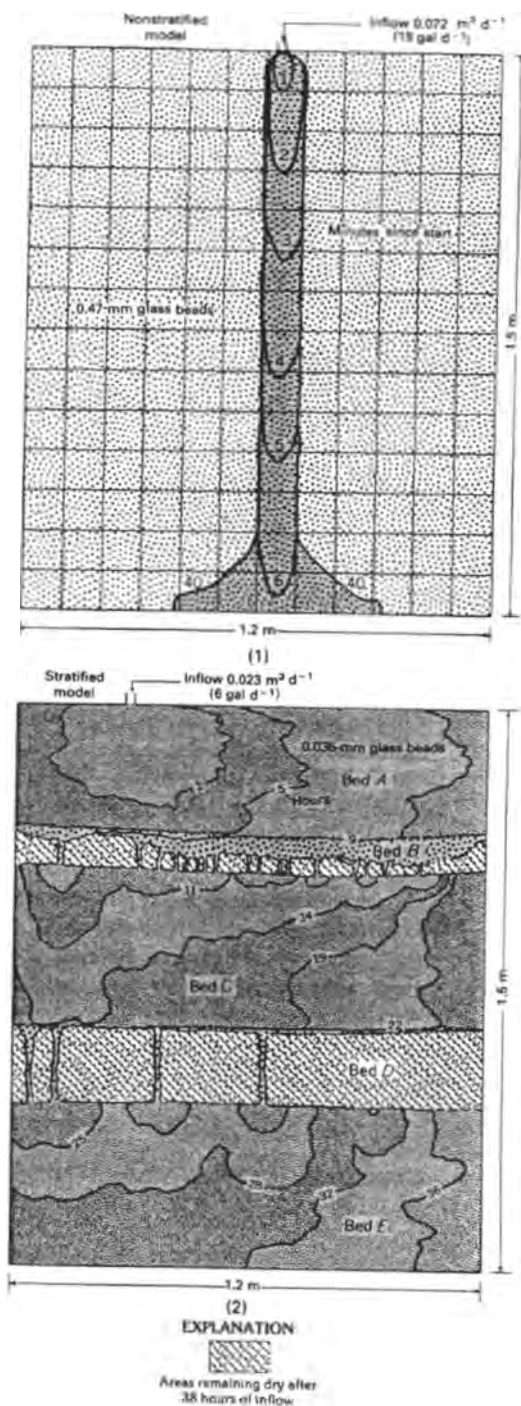
$$\frac{h_L}{L} = \frac{h_{t(1)} - h_{t(2)}}{z_{(1)} - z_{(2)}} = \frac{31 - 26}{32 - 28} = \frac{5 \text{ m}}{4 \text{ m}} = 1.25$$

This gradient includes both the gravitational gradient (dh/dl) and the capillary gradient ($(h_c - z)/z$). Because the head in tensiometer no. 1 exceeds that in tensiometer no. 2, we know that flow is vertically downward and that the gravitational gradient is 1/1, or 1. Therefore, the capillary gradient is 0.25 m m^{-1} ($1.25 - 1.00$).



The effective hydraulic conductivity (K_e) is the hydraulic conductivity of material that is not completely saturated. It is thus less than the (saturated) hydraulic conductivity (K_s) for the material. Sketch 4 shows the relation between degree of saturation and the ratio of saturated and unsaturated hydraulic conductivity for coarse sand. The hydraulic conductivity (K_s) of coarse sand is about 60 m d^{-1} .

STRATIFICATION AND UNSATURATED FLOW



Most sediments are deposited in layers (beds) that have a distinct grain size, sorting, or mineral composition. Where adjacent layers differ in one of these characteristics or more, the deposit is said to be *stratified*, and its layered structure is referred to as *stratification*.

The layers comprising a stratified deposit commonly differ from one another in both grain size and sorting and, consequently, differ from one another in hydraulic conductivity. These differences in hydraulic conductivity significantly affect both the percolation of water across the unsaturated zone and the movement of ground water.

In most areas, the unsaturated zone is composed of horizontal or nearly horizontal layers. The movement of water, on the other hand, is predominantly in a vertical direction. In many ground-water problems, and especially in those related to the release of pollutants at the land surface, the effect of stratification on movement of fluids across the unsaturated zone is of great importance.

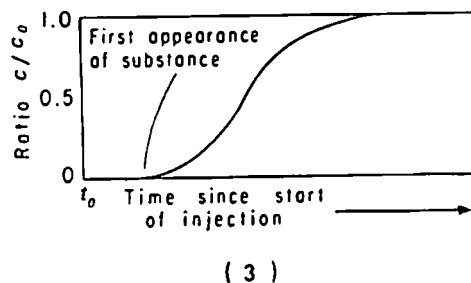
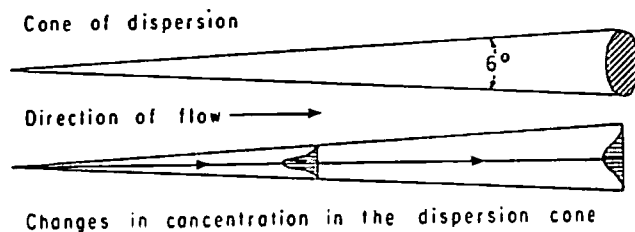
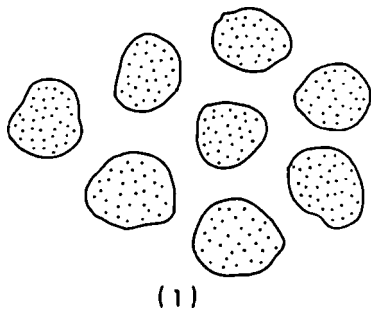
The manner in which water moves across the unsaturated zone has been studied by using models containing glass beads. One model (1) contained beads of a single size representing a nonstratified deposit, and another (2) consisted of five layers, three of which were finer grained and more impermeable than the other two. The dimensions of the models were about $1.5 \text{ m} \times 1.2 \text{ m} \times 76 \text{ mm}$.

In the nonstratified model, water introduced at the top moved vertically downward through a zone of constant width to the bottom of the model (1). In the stratified model, beds A, C, and E consisted of silt-sized beads (diameters of 0.036 mm) having a capillary height (h_c) of about 1,000 mm and a hydraulic conductivity (K) of 0.8 m d^{-1} . Beds B and D consisted of medium-sand-sized beads (diameters of 0.47 mm) having a capillary height of about 250 mm and a hydraulic conductivity of 82 m d^{-1} .

Because of the strong capillary force and the low hydraulic conductivity in bed A, the water spread laterally at almost the same rate as it did vertically, and it did not begin to enter bed B until 9 hours after the start of the experiment. At that time, the capillary saturation in bed A had reached a level where the unsatisfied (remaining) capillary pull in bed A was the same as that in bed B. In other words, z in bed A at that time equaled 1,000 mm – 250 mm, or 750 mm. (For a definition of z , see "Capillarity and Unsaturated Flow.")

Because the hydraulic conductivity of bed B was 100 times that of bed A, water moved across bed B through narrow vertical zones. We can guess that the glass beads in these zones were packed somewhat more tightly than those in other parts of the beds,

Dispersion in a granular deposit



In the saturated zone, all interconnected openings are full of water, and the water moves through these openings in the direction controlled by the hydraulic gradient. Movement in the saturated zone may be either laminar or turbulent. In *laminar flow*, water particles move in an orderly manner along streamlines. In *turbulent flow*, water particles move in a disordered, highly irregular manner, which results in a complex mixing of the particles. Under natural hydraulic gradients, turbulent flow occurs only in large openings such as those in gravel, lava flows, and limestone caverns. Flows are laminar in most granular deposits and fractured rocks.

In laminar flow in a granular medium, the different streamlines converge in the narrow necks between particles and diverge in the larger interstices (1). Thus, there is some intermingling of streamlines, which results in transverse dispersion—that is, dispersion at right angles to the direction of ground-water flow. Also, differences in velocity result from friction between the water and the rock particles. The slowest rate of movement occurs adjacent to the particles, and the fastest rate occurs in the center of pores. The resulting dispersion is longitudinal—that is, in the direction of flow.

Danel (1953) found that dye injected at a point in a homogeneous and isotropic granular medium dispersed laterally in the shape of a cone about 6° wide (2). He also found that the concentration of dye over a plane at any given distance from the inlet point is a bell-shaped curve similar to the normal probability curve. Because of transverse and longitudinal dispersion, the peak concentration decreased in the direction of flow.

The effect of longitudinal dispersion can also be observed from the change in concentration of a substance (C) downstream from a point at which the substance is being injected constantly at a concentration of C_0 . The concentration rises slowly at first as the "fastest" streamlines arrive and then rises rapidly until the concentration reaches about $0.7 C_0$, at which point the rate of increase in concentration begins to decrease (3).

Dispersion is important in the study of ground-water pollution. However, it is difficult to measure in the field because the rate and direction of movement of wastes are also affected by stratification, ion exchange, filtration, and other conditions and processes. Stratification and areal differences in lithology and other characteristics of aquifers and confining beds actually result in much greater lateral and longitudinal dispersion than that measured by Danel for a homogeneous and isotropic medium.

GROUND-WATER MOVEMENT AND TOPOGRAPHY

It is desirable, wherever possible, to determine the position of the water table and the direction of ground-water movement. To do so, it is necessary to determine the altitude, or the height above a datum plane, of the water level in wells. However, in most areas, general but very valuable conclusions about the direction of ground-water movement can be derived from observations of land-surface topography.

Gravity is the dominant driving force in ground-water movement. Under natural conditions, ground water moves "down-hill" until, in the course of its movement, it reaches the land surface at a spring or through a seep along the side or bottom of a stream channel or an estuary.

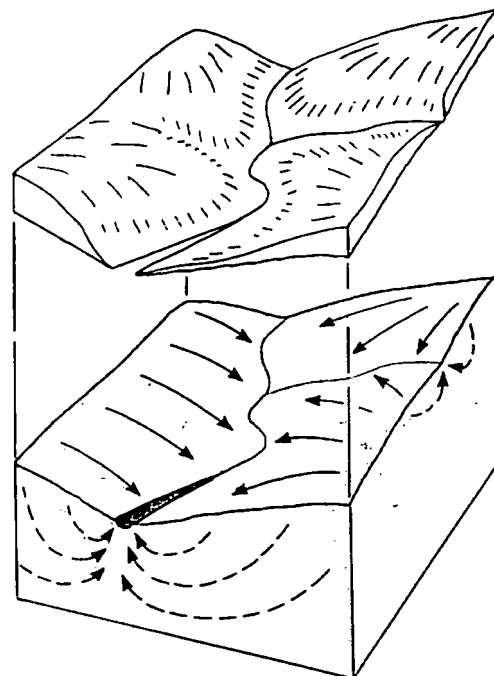
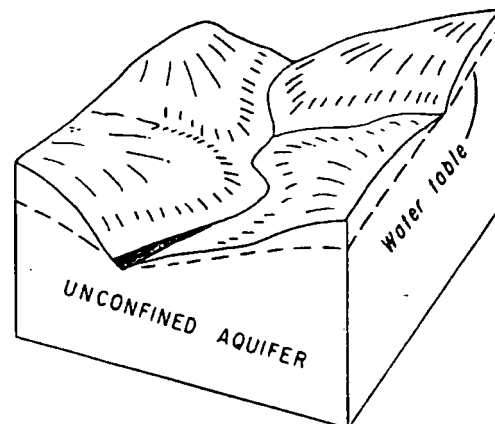
Thus, ground water in the shallowest part of the saturated zone moves from interstream areas toward streams or the coast. If we ignore minor surface irregularities, we find that the slope of the land surface is also toward streams or the coast. The depth to the water table is greater along the divide between streams than it is beneath the flood plain. In effect, the water table usually is a subdued replica of the land surface.

In areas where ground water is used for domestic and other needs requiring good-quality water, septic tanks, sanitary landfills, waste ponds, and other waste-disposal sites should not be located uphill from supply wells.

The potentiometric surface of confined aquifers, like the water table, also slopes from recharge areas to discharge areas. Shallow confined aquifers, which are relatively common along the Atlantic Coastal Plain, share both recharge and discharge areas with the surficial unconfined aquifers. This sharing may not be the case with the deeper confined aquifers. The principal recharge areas for these are probably in their outcrop areas near the western border of the Coastal Plain, and their discharge areas are probably near the heads of the estuaries along the major streams. Thus, movement of water through these aquifers is in a general west to east direction, where it has not been modified by withdrawals.

In the western part of the conterminous United States, and especially in the alluvial basins region, conditions are more variable than those described above. In this area, streams flowing from mountain ranges onto alluvial plains lose water to the alluvial deposits; thus, ground water in the upper part of the saturated zone flows down the valleys and at an angle away from the streams.

Ground water is normally hidden from view; as a consequence, many people have difficulty visualizing its occurrence and movement. This difficulty adversely affects their ability to understand and to deal effectively with ground-water-related problems. This problem can be partly solved



through the use of flow nets, which are one of the most effective means yet devised for illustrating conditions in ground-water systems.

GROUND-WATER FLOW NETS

Flow nets consist of two sets of lines. One set, referred to as *equipotential lines*, connects points of equal head and thus represents the height of the water table, or the potentiometric surface of a confined aquifer, above a datum plane. The second set, referred to as *flow lines*, depicts the idealized paths followed by particles of water as they move through the aquifer. Because ground water moves in the direction of the steepest hydraulic gradient, flow lines in isotropic aquifers are perpendicular to equipotential lines—that is, flow lines cross equipotential lines at right angles.

There are an infinite number of equipotential lines and flow lines in an aquifer. However, for purposes of flow-net analysis, only a few of each set need be drawn. Equipotential lines are drawn so that the drop in head is the same between adjacent pairs of lines. Flow lines are drawn so that the flow is equally divided between adjacent pairs of lines and so that, together with the equipotential lines, they form a series of "squares."

Flow nets not only show the direction of ground-water movement but can also, if they are drawn with care, be used to estimate the quantity of water in transit through an aquifer. According to Darcy's law, the flow through any "square" is

$$q = Kbw \left(\frac{dh}{dl} \right) \quad (1)$$

and the total flow through any set or group of "squares" is

$$Q = nq \quad (2)$$

where K is hydraulic conductivity, b is aquifer thickness at the midpoint between equipotential lines, w is the distance be-

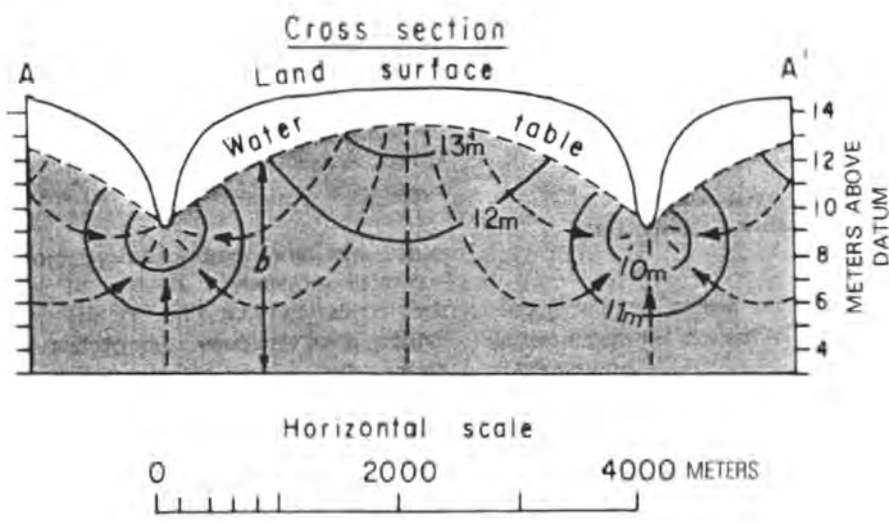
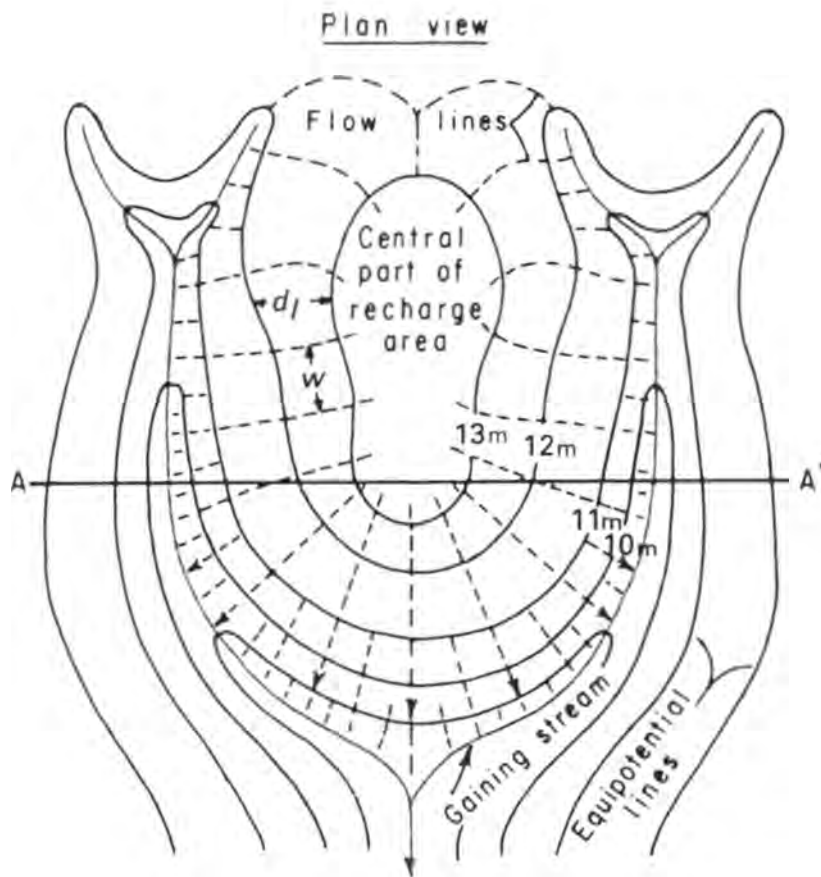
tween flow lines, dh is the difference in head between equipotential lines, dl is the distance between equipotential lines, and n is the number of squares through which the flow occurs.

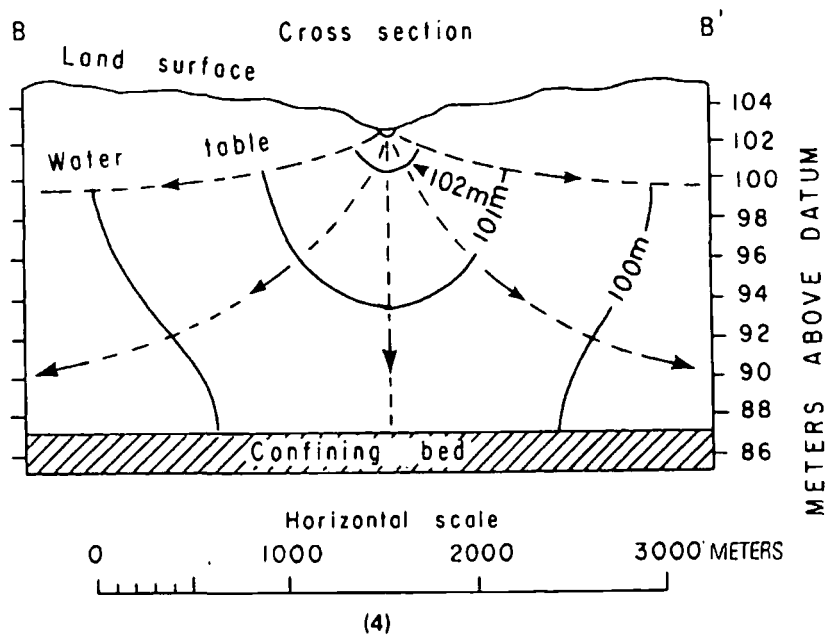
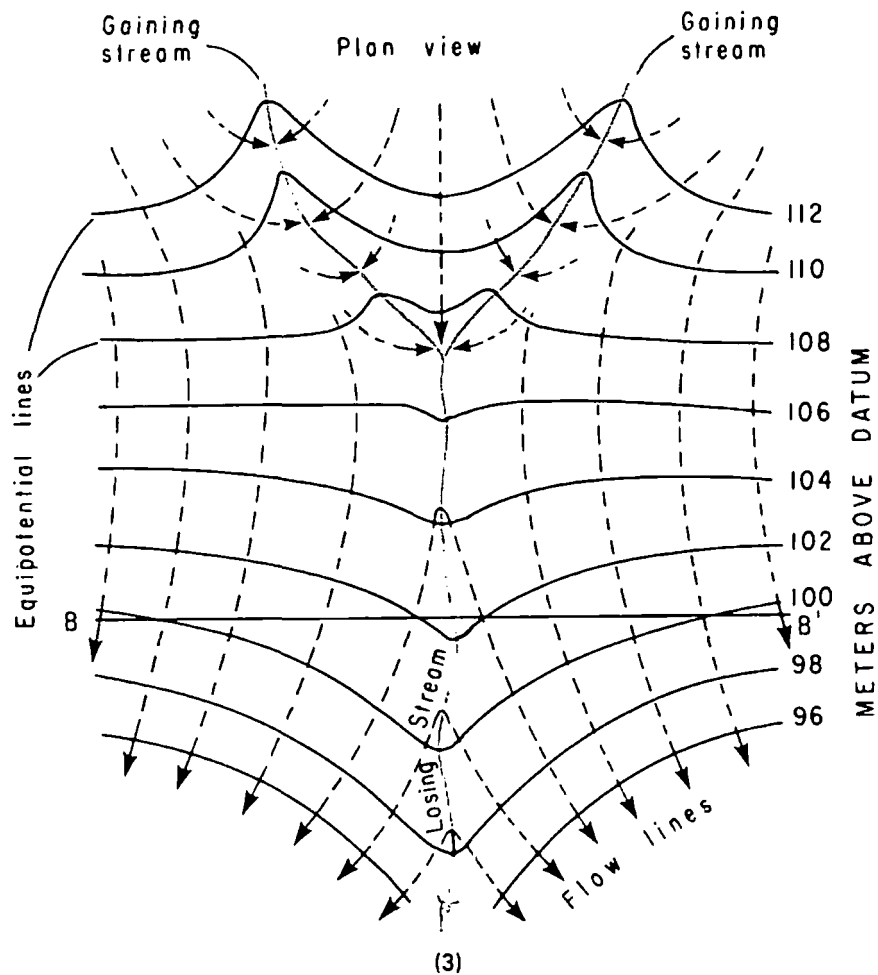
Drawings 1 and 2 show a flow net in both plan view and cross section for an area underlain by an unconfined aquifer composed of sand. The sand overlies a horizontal confining bed, the top of which occurs at an elevation 3 m above the datum plane. The fact that some flow lines originate in the area in which heads exceed 13 m indicates the presence of recharge to the aquifer in this area. The relative positions of the land surface and the water table in sketch 2 suggest that recharge occurs throughout the area, except along the stream valleys. This suggestion is confirmed by the fact that flow lines also originate in areas where heads are less than 13 m.

As sketches 1 and 2 show, flow lines originate in recharge areas and terminate in discharge areas. Closed contours (equipotential lines) indicate the central parts of recharge areas but do not normally indicate the limits of the areas.

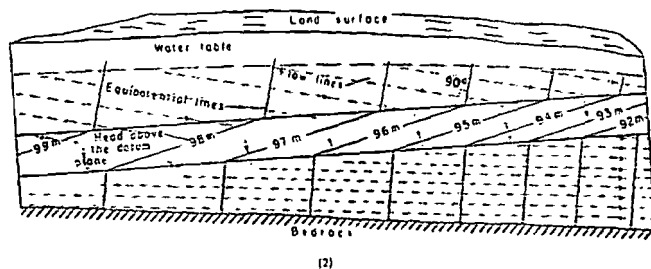
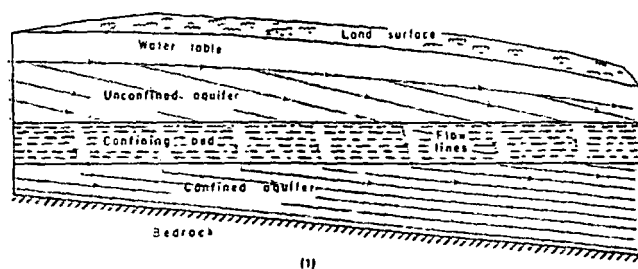
In the cross-sectional view in sketch 2, heads decrease downward in the recharge area and decrease upward in the discharge area. Consequently, the deeper a well is drilled in a recharge area, the lower the water level in the well stands below land surface. The reverse is true in discharge areas. Thus, in a discharge area, if a well is drilled deeply enough in an unconfined aquifer, the well may flow above land surface. Consequently, a flowing well does not necessarily indicate artesian conditions.

Drawings 3 and 4 show equipotential lines and flow lines in the vicinity of a stream that gains water in its headwaters and loses water as it flows downstream. In the gaining reaches, the equipotential lines form a V pointing upstream; in the losing reach, they form a V pointing downstream.





GROUND-WATER MOVEMENT AND STRATIFICATION



Nearly all ground-water systems include both aquifers and confining beds. Thus, ground-water movement through these systems involves flow not only through the aquifers but also across the confining beds (1).

The hydraulic conductivities of aquifers are tens to thousands of times those of confining beds. Thus, aquifers offer the least resistance to flow, the result being that, for a given rate of flow, the head loss per unit of distance along a flow line is tens to thousands of times less in aquifers than it is in confining beds. Consequently, lateral flow in confining beds usually is negligible, and flow lines tend to "concentrate" in aquifers and be parallel to aquifer boundaries (2).

Differences in the hydraulic conductivities of aquifers and confining beds cause a refraction or bending of flow lines at their boundaries. As flow lines move from aquifers into confining beds, they are refracted toward the direction perpendicular to the boundary. In other words, they are refracted in the direction that produces the shortest flow path in the confining bed. As the flow lines emerge from the confining bed, they are refracted back toward the direction parallel to the boundary (1).

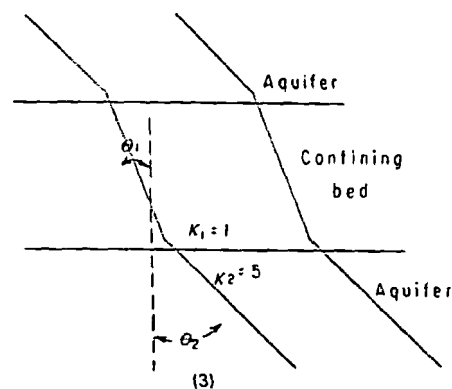
The angles of refraction (and the spacing of flow lines in adjacent aquifers and confining beds) are proportional to the differences in hydraulic conductivities (K) (3) such that

$$\frac{\tan \theta_1}{\tan \theta_2} = \frac{K_1}{K_2}$$

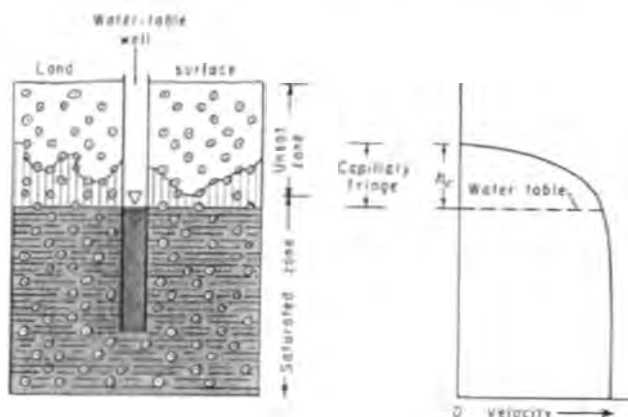
In cross section, the water table is a flow line. It represents a bounding surface for the ground-water system; thus, in the development of many ground-water flow equations, it is assumed to be coincident with a flow line. However, during periods when recharge is arriving at the top of the capillary fringe, the water table is also the point of origin of flow lines (1).

The movement of water through ground-water systems is controlled by the vertical and horizontal hydraulic conductivities and thicknesses of the aquifers and confining beds and the hydraulic gradients. The maximum difference in head exists between the central parts of recharge areas and discharge areas. Because of the relatively large head loss that occurs as water moves across confining beds, the most vigorous circulation of ground water normally occurs through the shallowest aquifers. Movement becomes more and more lethargic as depth increases.

The most important exceptions to the general situation described in the preceding paragraph are those systems in which one or more of the deeper aquifers have transmissivities significantly larger than those of the surficial and other shallower aquifers. Thus, in eastern North Carolina, the Castle Hayne Limestone, which occurs at depths ranging from about 10 to about 75 m below land surface, is the dominant aquifer because of its very large transmissivity, although it is overlain in most of the area by one or more less permeable aquifers.



GROUND-WATER VELOCITY



The rate of movement of ground water is important in many problems, particularly those related to pollution. For example, if a harmful substance is introduced into an aquifer upgradient from a supply well, it becomes a matter of great urgency to estimate when the substance will reach the well.

The rate of movement of ground water is greatly overestimated by many people, including those who think in terms of ground water moving through "veins" and underground rivers at the rates commonly observed in surface streams. It would be more appropriate to compare the rate of movement of ground water to the movement of water in the middle of a very large lake being drained by a very small stream.

The ground-water velocity equation can be derived from a combination of Darcy's law and the velocity equation of hydraulics.

$$Q = KA \left(\frac{dh}{dl} \right) \quad (\text{Darcy's law})$$

$$Q = Av \quad (\text{velocity equation})$$

where Q is the rate of flow or volume per unit of time, K is the hydraulic conductivity, A is the cross-sectional area, at a right angle to the flow direction, through which the flow Q occurs, dh/dl is the hydraulic gradient, and v is the Darcian velocity, which is the average velocity of the entire cross-sectional area. Combining these equations, we obtain

$$Av = KA \left(\frac{dh}{dl} \right)$$

Canceling the area terms, we find that

$$v = K \left(\frac{dh}{dl} \right)$$

Because this equation contains terms for hydraulic conductivity and gradient only, it is not yet a complete expression of

ground-water velocity. The missing term is porosity (n) because, as we know, water moves only through the openings in a rock. Adding the porosity term, we obtain

$$v = \frac{Kdh}{ndl} \quad (1)$$

In order to demonstrate the relatively slow rate of ground-water movement, equation 1 is used to determine the rate of movement through an aquifer and a confining bed.

1. Aquifer composed of coarse sand

$$K = 60 \text{ m/d}$$

$$dh/dl = 1 \text{ m/1,000 m}$$

$$n = 0.20$$

$$v = \frac{K}{n} \times \frac{dh}{dl} = \frac{60 \text{ m}}{0.20} \times \frac{1}{1,000 \text{ m}} = \frac{60 \text{ m}^2}{200 \text{ m d}} = 0.3 \text{ m d}^{-1}$$

2. Confining bed composed of clay

$$K = 0.0001 \text{ m/d}$$

$$dh/dl = 1 \text{ m/10 m}$$

$$n = 0.50$$

$$v = \frac{0.0001 \text{ m}}{0.50} \times \frac{1}{10 \text{ m}} = \frac{0.0001 \text{ m}^2}{5 \text{ m d}} = 0.00002 \text{ m d}^{-1}$$

Velocities calculated with equation 1 are, at best, average values. Where ground-water pollution is involved, the fastest rates of movement may be several times the average rate. Also, the rates of movement in limestone caverns, lava tubes, and large rock fractures may approach those observed in surface streams.

Further, movement in unconfined aquifers is not limited to the zone below the water table or to the saturated zone. Water in the capillary fringe is subjected to the same hydraulic gradient that exists at the water table; water in the capillary fringe moves, therefore, in the same direction as the ground water.

As the accompanying sketch shows, the rate of lateral movement in the capillary fringe decreases in an upward direction and becomes zero at the top of the fringe. This consideration is important where unconfined aquifers are polluted with gasoline and other substances less dense than water.

TRANSMISSIVITY

The capacity of an aquifer to transmit water of the prevailing kinematic viscosity is referred to as its transmissivity. The transmissivity (T) of an aquifer is equal to the hydraulic conductivity of the aquifer multiplied by the saturated thickness of the aquifer. Thus,

$$T = Kb \quad (1)$$

where T is transmissivity, K is hydraulic conductivity, and b is aquifer thickness.

As is the case with hydraulic conductivity, transmissivity is also defined in terms of a unit hydraulic gradient.

If equation 1 is combined with Darcy's law (see "Hydraulic Conductivity"), the result is an equation that can be used to calculate the quantity of water (q) moving through a unit width (w) of an aquifer. Darcy's law is

$$q = KA \left(\frac{dh}{dl} \right)$$

Expressing area (A) as bw , we obtain

$$q = Kbw \left(\frac{dh}{dl} \right)$$

Next, expressing transmissivity (T) as Kb , we obtain

$$q = Tw \left(\frac{dh}{dl} \right) \quad (2)$$

Equation 2 modified to determine the quantity of water (Q) moving through a large width (W) of an aquifer is

$$Q = TwW \left(\frac{dh}{dl} \right)$$

or, if it is recognized that T applies to a unit width (w) of an aquifer, this equation can be stated more simply as

$$Q = TW \left(\frac{dh}{dl} \right) \quad (3)$$

If equation 3 is applied to sketch 1, the quantity of water flowing out of the right-hand side of the sketch can be calculated by using the values shown on the sketch, as follows:

$$T = Kb = \frac{50 \text{ m}}{d} \times \frac{100 \text{ m}}{1} = 5,000 \text{ m}^2 \text{ d}^{-1}$$

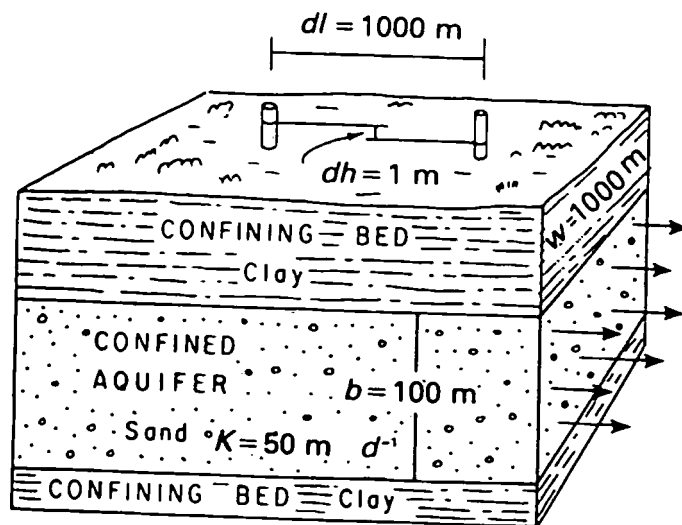
$$Q = TW \left(\frac{dh}{dl} \right) = \frac{5,000 \text{ m}^2}{d} \times \frac{1,000 \text{ m}}{1} \times \frac{1 \text{ m}}{1,000 \text{ m}} = 5,000 \text{ m}^3 \text{ d}^{-1}$$

Equation 3 is also used to calculate transmissivity, where the quantity of water (Q) discharging from a known width of aquifer can be determined as, for example, with streamflow measurements. Rearranging terms, we obtain

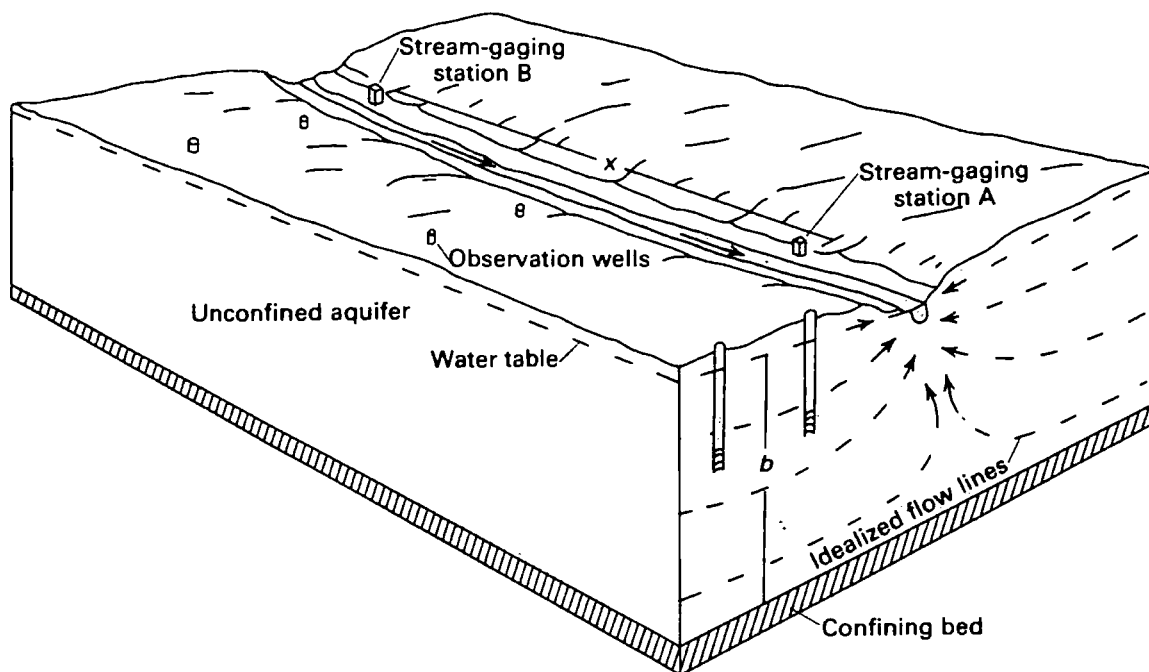
$$T = \frac{Q}{W} \left(\frac{dl}{dh} \right) \quad (4)$$

The units of transmissivity, as the preceding equation demonstrates, are

$$T = \frac{(\text{m}^3 \text{ d}^{-1})(\text{m})}{(\text{m})(\text{m})} = \frac{\text{m}^2}{\text{d}}$$



(1)



(2)

Sketch 2 illustrates the hydrologic situation that permits calculation of transmissivity through the use of stream discharge. The calculation can be made only during dry-weather (baseflow) periods, when all water in the stream is derived from ground-water discharge. For the purpose of this example, the following values are assumed:

Average daily flow at stream-gaging station A:	2.485 m ³ s ⁻¹
Average daily flow at stream-gaging station B:	2.355 m ³ s ⁻¹
Increase in flow due to ground-water discharge:	0.130 m ³ s ⁻¹
Total daily ground-water discharge to stream:	11,232 m ³ d ⁻¹
Discharge from half of aquifer (one side of the stream):	5,616 m ³ d ⁻¹
Distance (x) between stations A and B:	5,000 m
Average thickness of aquifer (b):	50 m
Average slope of the water table (dh/dl) determined from measurements in the observation wells:	1 m/2,000 m

By equation 4,

$$T = \frac{Q}{W} \times \frac{dl}{dh} = \frac{5,616 \text{ m}^3}{d \times 5,000 \text{ m}} \times \frac{2,000 \text{ m}}{1 \text{ m}} = 2,246 \text{ m}^2 \text{ d}^{-1}$$

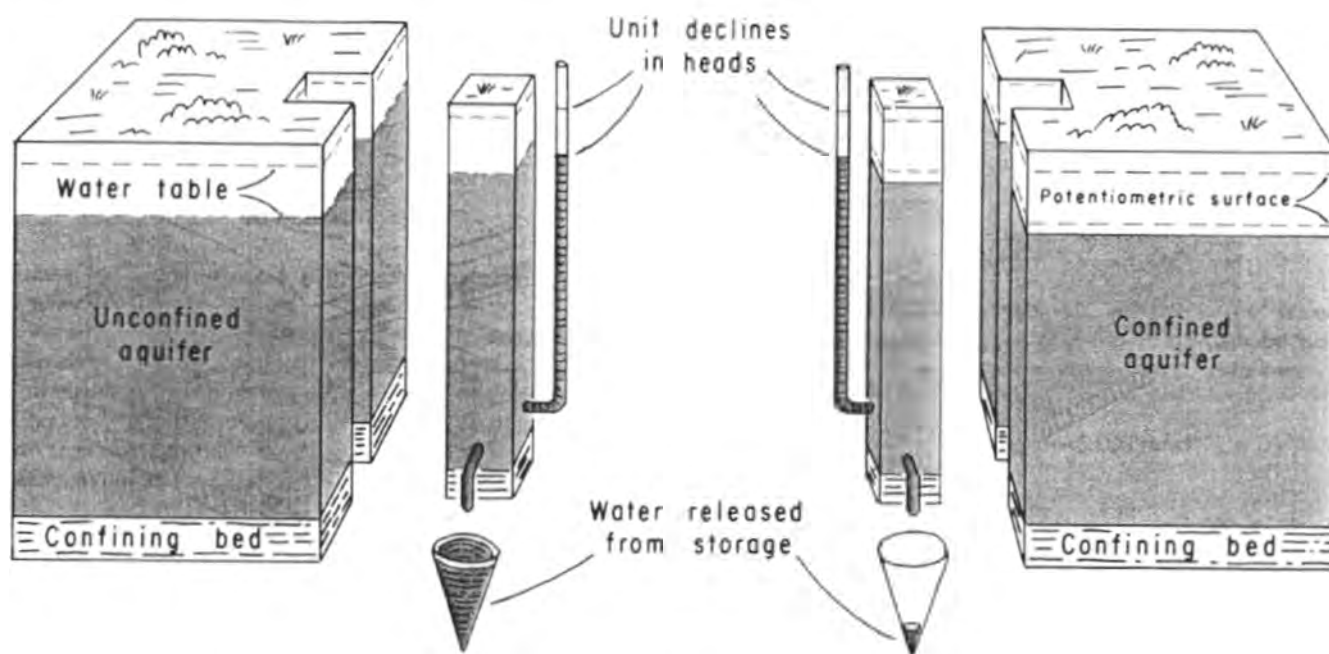
The hydraulic conductivity is determined from equation 1 as follows:

$$K = \frac{T}{b} = \frac{2,246 \text{ m}^2}{d \times 50 \text{ m}} = 45 \text{ m d}^{-1}$$

Because transmissivity depends on both K and b , its value differs in different aquifers and from place to place in the same aquifer. Estimated values of transmissivity for the principal aquifers in different parts of the country range from less than 1 m² d⁻¹ for some fractured sedimentary and igneous rocks to 100,000 m² d⁻¹ for cavernous limestones and lava flows.

Finally, transmissivity replaces the term "coefficient of transmissibility" because, by convention, an aquifer is transmissive, and the water in it is transmissible.

STORAGE COEFFICIENT



(1)

The abilities (capacities) of water-bearing materials to store and to transmit water are their most important hydraulic properties. Depending on the intended use of the information, these properties are given either in terms of a unit cube of the material or in terms of a unit prism of an aquifer.

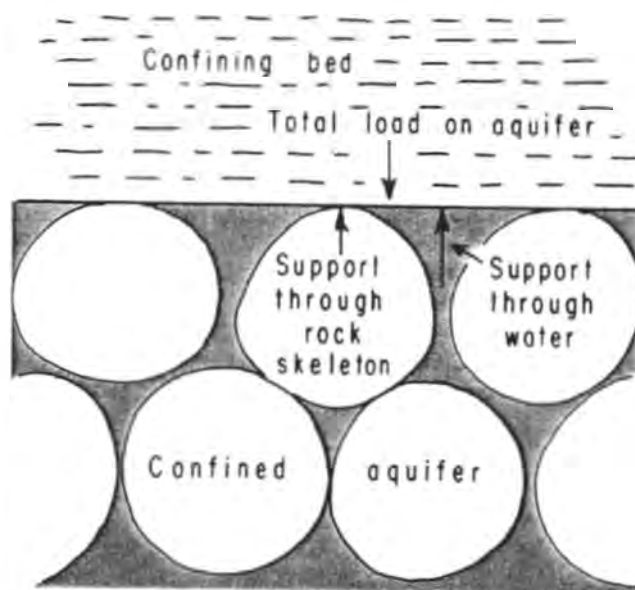
Property	Unit cube of material	Unit prism of aquifer
Transmissive capacity	Hydraulic conductivity (K)	Transmissivity (T)
Available storage	Specific yield (S_y)	Storage coefficient (S)

The storage coefficient (S) is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storage coefficient is a dimensionless unit, as the following equation shows, in which the units in the numerator and the denominator cancel:

$$S = \frac{\text{volume of water}}{(\text{unit area})(\text{unit head change})} = \frac{(\text{m}^3)}{(\text{m}^2)(\text{m})} = \frac{\text{m}^3}{\text{m}^3}$$

The size of the storage coefficient depends on whether the aquifer is confined or unconfined (1). If the aquifer is confined, the water released from storage when the head declines comes from expansion of the water and from compression of the aquifer. Relative to a confined aquifer, the expansion of a given volume of water in response to a decline in pressure is very small. In a confined aquifer having a porosity of 0.2 and containing water at a temperature of about 15°C, expansion of the water alone releases about $3 \times 10^{-7} \text{ m}^3$ of water per cubic meter of aquifer per meter of decline in head. To determine the storage coefficient of an aquifer due to expansion of

the water, it is necessary to multiply the aquifer thickness by 3×10^{-7} . Thus, if only the expansion of water is considered, the storage coefficient of an aquifer 100 m thick would be 3×10^{-5} . The storage coefficient of most confined aquifers ranges from about 10^{-5} to 10^{-3} (0.00001 to 0.001). The difference between these values and the value due to expansion of the water is attributed to compression of the aquifer.



(2)

Sketch 2 will aid in understanding this phenomenon. It shows a microscopic view of the contact between an aquifer and the overlying confining bed. The total load on the top of the aquifer is supported partly by the solid skeleton of the aquifer and partly by the hydraulic pressure exerted by the water in the aquifer. When the water pressure declines, more of the load must be supported by the solid skeleton. As a result, the rock particles are distorted, and the pore space is reduced. The water forced from the pores when their volume is reduced represents the part of the storage coefficient due to compression of the aquifer.

If the aquifer is unconfined, the predominant source of water is from gravity drainage of the sediments through which the decline in the water table occurs. In an unconfined aquifer, the volume of water derived from expansion of the water and compression of the aquifer is negligible. Thus, in such an aquifer, the storage coefficient is virtually equal to the specific yield and ranges from about 0.1 to about 0.3.

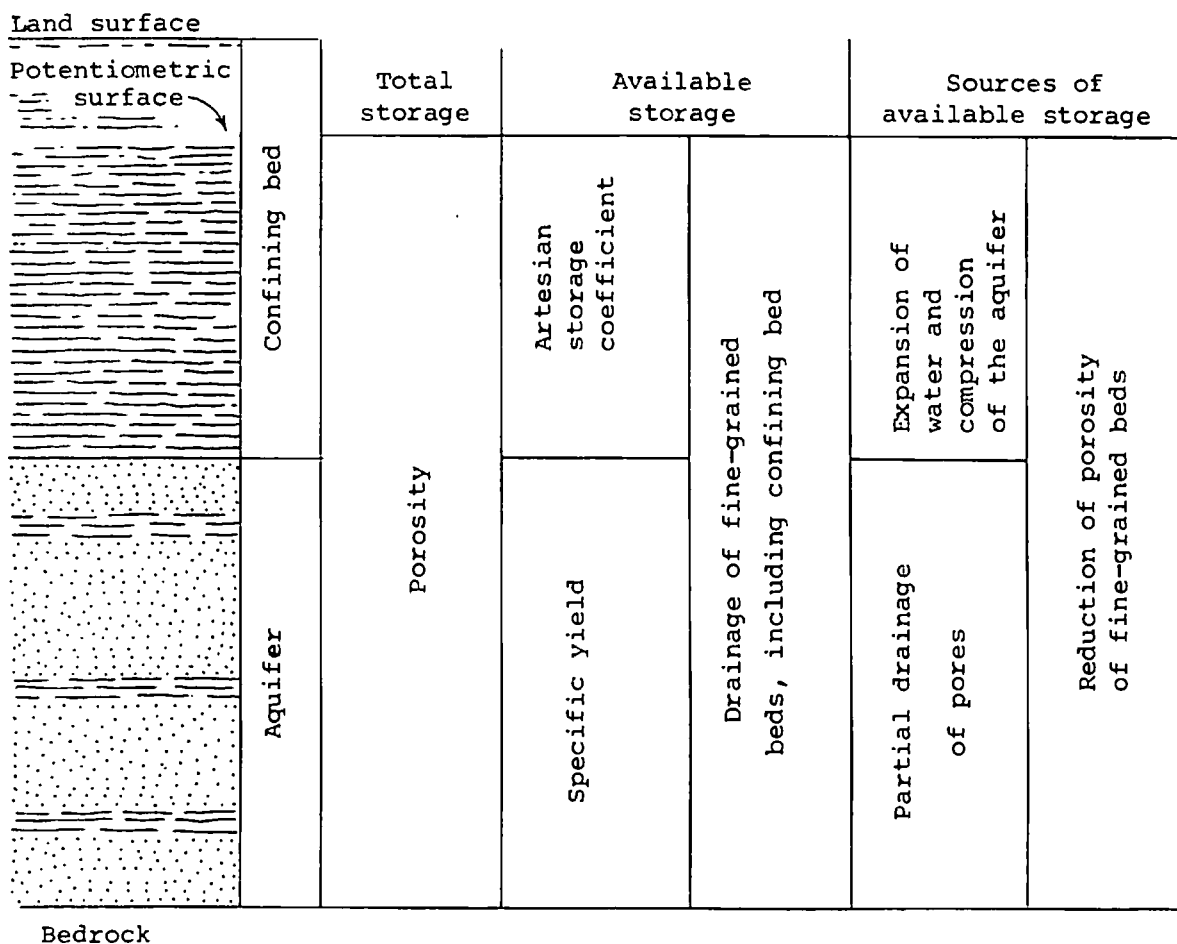
Because of the difference in the sources of storage, the storage coefficient of unconfined aquifers is 100 to 10,000 times the storage coefficient of confined aquifers (1). However, if water levels in an area are reduced to the point where

an aquifer changes from a confined condition to an unconfined condition, the storage coefficient of the aquifer immediately increases from that of a confined aquifer to that of an unconfined aquifer.

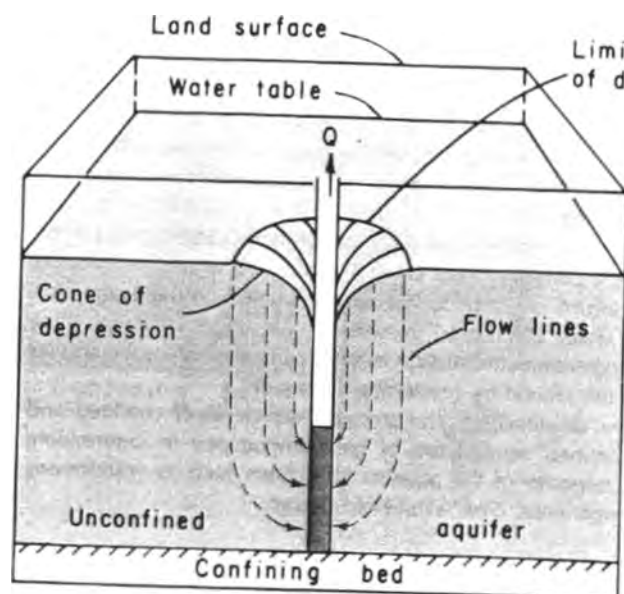
Long-term withdrawals of water from many confined aquifers result in drainage of water both from clay layers within the aquifer and from adjacent confining beds. This drainage increases the load on the solid skeleton and results in compression of the aquifer and subsidence of the land surface. Subsidence of the land surface caused by drainage of clay layers has occurred in Arizona, California, Texas, and other areas.

The potential sources of water in a two-unit ground-water system consisting of a confining bed and a confined aquifer are shown in sketch 3. The sketch is based on the assumption that water is removed in two separate stages—the first while the potentiometric surface is lowered to the top of the aquifer and the second by dewatering the aquifer.

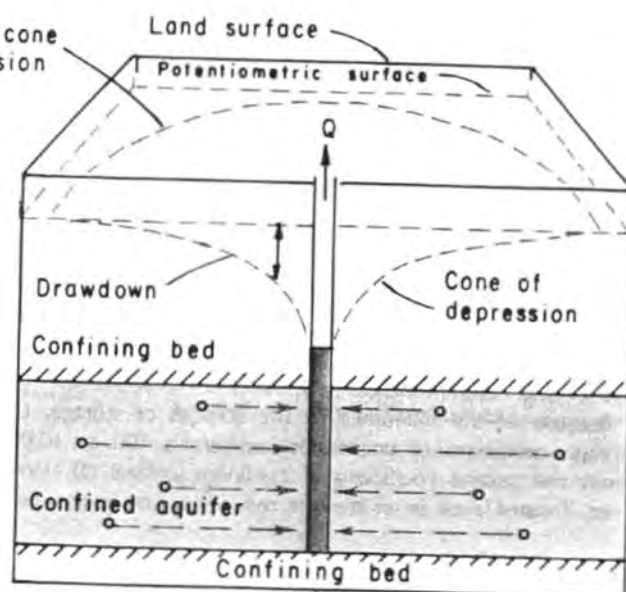
The differences in the storage coefficients of confined and unconfined aquifers are of great importance in determining the response of the aquifers to stresses such as withdrawals through wells. (See "Well-Field Design.")



CONE OF DEPRESSION



(1)



(2)

Both wells and springs serve as sources of ground-water supply. However, most springs having yields large enough to meet municipal, industrial, and large commercial and agricultural needs occur only in areas underlain by cavernous limestones and lava flows. Therefore, most ground-water needs are met by withdrawals from wells.

The response of aquifers to withdrawals from wells is an important topic in ground-water hydrology. When withdrawals start, the water level in the well begins to decline as water is removed from storage in the well. The head in the well falls below the level in the surrounding aquifer. As a result, water begins to move from the aquifer into the well. As pumping continues, the water level in the well continues to decline, and the rate of flow into the well from the aquifer continues to increase until the rate of inflow equals the rate of withdrawal.

The movement of water from an aquifer into a well results in the formation of a cone of depression (1) (2). Because water must converge on the well from all directions and because the area through which the flow occurs decreases toward the well, the hydraulic gradient must get steeper toward the well.

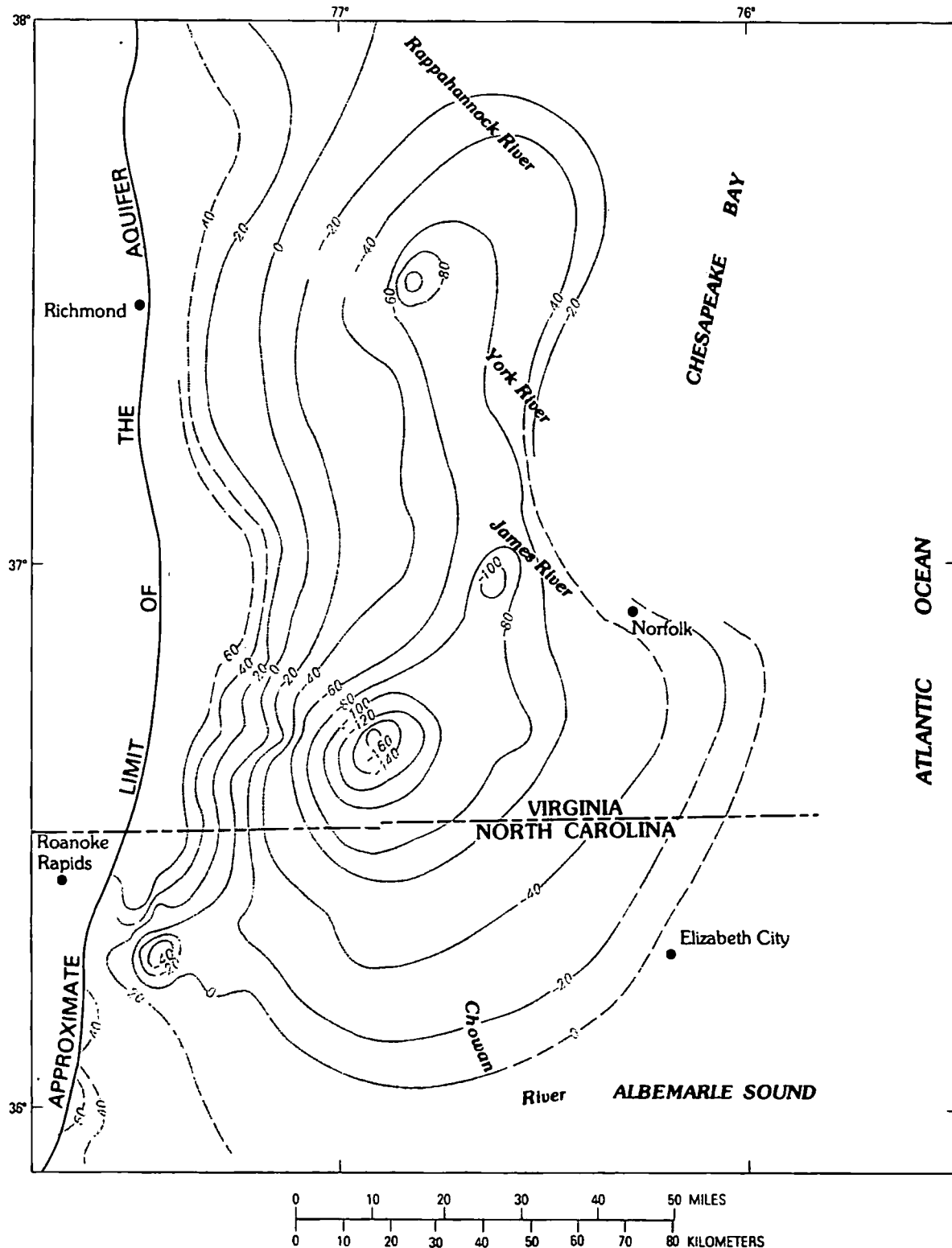
Several important differences exist between the cones of depression in confined and unconfined aquifers. Withdrawals from an unconfined aquifer result in drainage of water from the rocks through which the water table declines as the cone of depression forms (1). Because the storage coefficient of an

unconfined aquifer equals the specific yield of the aquifer material, the cone of depression expands very slowly. On the other hand, dewatering of the aquifer results in a decrease in transmissivity, which causes, in turn, an increase in drawdown both in the well and in the aquifer.

Withdrawals from a confined aquifer cause a drawdown in artesian pressure but do not (normally) cause a dewatering of the aquifer (2). The water withdrawn from a confined aquifer is derived from expansion of the water and compression of the rock skeleton of the aquifer. (See "Storage Coefficient.") The very small storage coefficient of confined aquifers results in a very rapid expansion of the cone of depression. Consequently, the mutual interference of expanding cones around adjacent wells occurs more rapidly in confined aquifers than it does in unconfined aquifers.

Cones of depression caused by large withdrawals from extensive confined aquifers can affect very large areas. Sketch 3 shows the overlapping cones of depression that existed in 1981 in an extensive confined aquifer composed of unconsolidated sands and interbedded silt and clay of Cretaceous age in the central part of the Atlantic Coastal Plain. The cones of depression are caused by withdrawals of about $277,000 \text{ m}^3 \text{ d}^{-1}$ ($73,000,000 \text{ gal d}^{-1}$) from well fields in Virginia and North Carolina. (See "Source of Water Derived From Wells.")

POTENTIOMETRIC SURFACE OF THE LOWERMOST CRETACEOUS
AQUIFER IN SOUTHEASTERN VIRGINIA AND NORTHEASTERN NORTH CAROLINA



EXPLANATION
Water levels are in feet
NATIONAL GEODETIC VERTICAL DATUM 1929
(3)

SOURCE OF WATER DERIVED FROM WELLS

Both the economical development and the effective management of any ground-water system require an understanding of the response of the system to withdrawals from wells. The first concise description of the hydrologic principles involved in this response was presented by C. V. Theis in a paper published in 1940.

Theis pointed out that the response of an aquifer to withdrawals from wells depends on:

1. The rate of expansion of the cone of depression caused by the withdrawals, which depends on the transmissivity and the storage coefficient of the aquifer.
2. The distance to areas in which the rate of water discharging from the aquifer can be reduced.
3. The distance to recharge areas in which the rate of recharge can be increased.

Over a sufficiently long period of time under natural conditions—that is, before the start of withdrawals—the discharge from every ground-water system equals the recharge to it (1). In other words,

$$\text{natural discharge (D)} = \text{natural recharge (R)}$$

In the eastern part of the United States and in the more humid areas in the West, the amount and distribution of precipitation are such that the period of time over which discharge and recharge balance may be less than a year or, at most, a few years. In the drier parts of the country—that is, in the areas that generally receive less than about 500 mm of precipitation annually—the period over which discharge and recharge balance may be several years or even centuries. Over shorter periods of time, differences between discharge and recharge involve changes in ground-water storage. In other words, when discharge exceeds recharge, ground-water storage (S) is reduced by an amount ΔS equal to the difference between discharge and recharge. Thus,

$$D = R + \Delta S$$

Conversely, when recharge exceeds discharge, ground-water storage is increased. Thus,

$$D = R - \Delta S$$

When withdrawal through a well begins, water is removed from storage in its vicinity as the cone of depression develops (2). Thus, the withdrawal (Q) is balanced by a reduction in ground-water storage. In other words,

$$Q = \Delta S$$

As the cone of depression expands outward from the pumping well, it may reach an area where water is discharging from

the aquifer. The hydraulic gradient will be reduced toward the discharge area, and the rate of natural discharge will decrease (3). To the extent that the decrease in natural discharge compensates for the pumpage, the rate at which water is being removed from storage will also decrease, and the rate of expansion of the cone of depression will decline. If and when the reduction in natural discharge (ΔD) equals the rate of withdrawal (Q), a new balance will be established in the aquifer. This balance in symbolic form is

$$(D - \Delta D) + Q = R$$

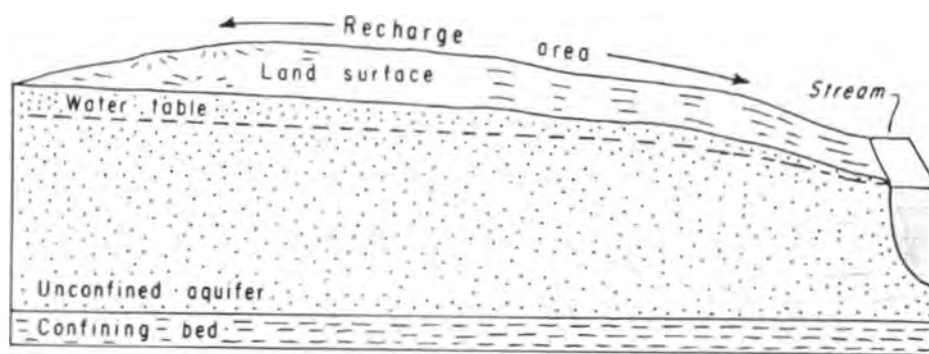
Conversely, if the cone of depression expands into a recharge area rather than into a natural discharge area, the hydraulic gradient between the recharge area and the pumping well will be increased. If, under natural conditions, more water was available in the recharge area than the aquifer could accept (the condition that Theis referred to as one of rejected recharge), the increase in the gradient away from the recharge area will permit more recharge to occur, and the rate of growth of the cone of depression will decrease. If and when the increase in recharge (ΔR) equals the rate of withdrawal (Q), a new balance will be established in the aquifer, and expansion of the cone of depression will cease. The new balance in symbolic form is

$$D + Q = R + \Delta R$$

In the eastern part of the United States, gaining streams are relatively closely spaced, and areas in which rejected recharge occurs are relatively unimportant. In this region, the growth of cones of depression first commonly causes a reduction in natural discharge. If the pumping wells are near a stream or if the withdrawals are continued long enough, ground-water discharge to a stream may be stopped entirely in the vicinity of the wells, and water may be induced to move from the stream into the aquifer (4). In other words, the tendency in this region is for withdrawals to change discharge areas into recharge areas. This consideration is important where the streams contain brackish or polluted water or where the streamflow is committed or required for other purposes.

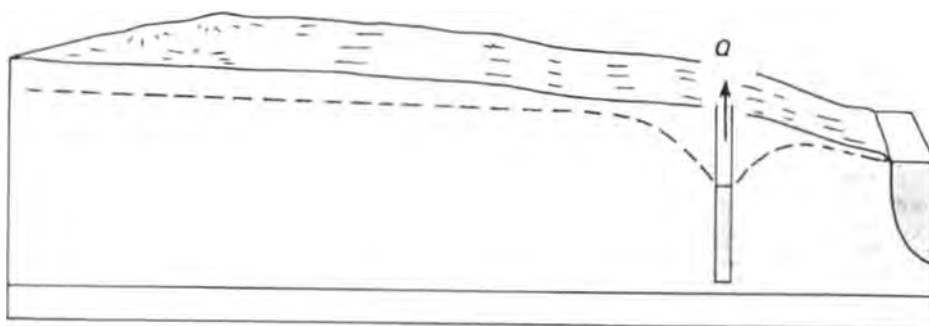
To summarize, the withdrawal of ground water through a well reduces the water in storage in the source aquifer during the growth of the cone of depression. When and if the cone of depression ceases to expand, the rate of withdrawal is being balanced by a reduction in the rate of natural discharge and (or) by an increase in the rate of recharge. Under this condition,

$$Q = \Delta D + \Delta R$$



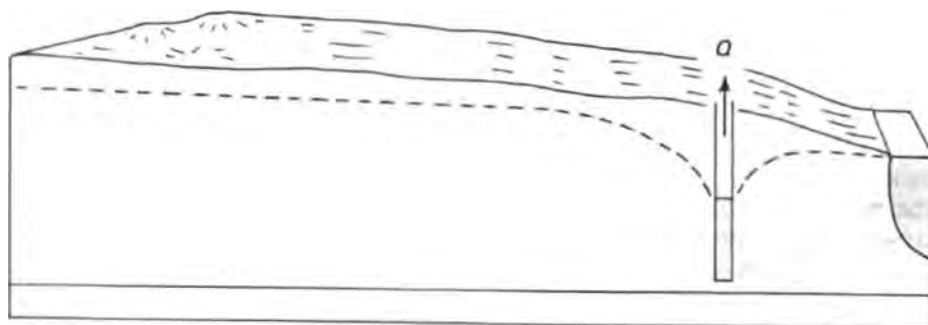
$$\text{Discharge } (D) = \text{Recharge } (R)$$

(1)



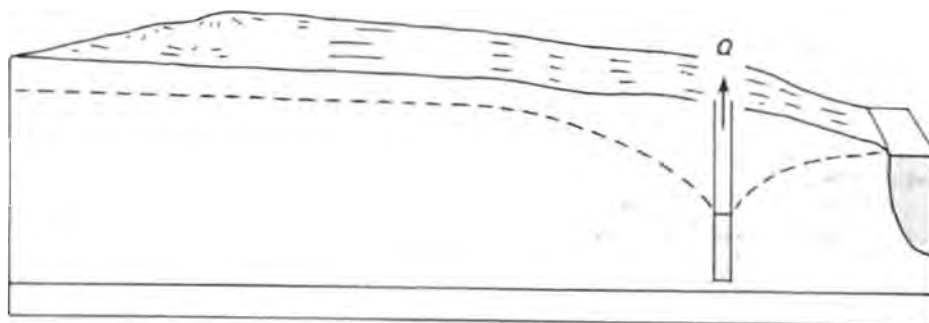
$$\text{Withdrawal } (Q) = \text{Reduction in storage } (\Delta S)$$

(2)



$$\text{Withdrawal } (Q) = \text{Reduction in storage } (\Delta S) + \text{Reduction in discharge } (\Delta D)$$

(3)

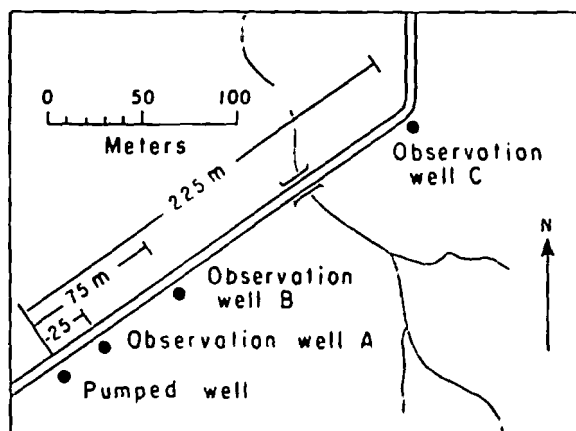


$$\text{Withdrawal } (Q) = \text{Reduction in discharge } (\Delta D) + \text{Increase in recharge } (\Delta R)$$

(4)

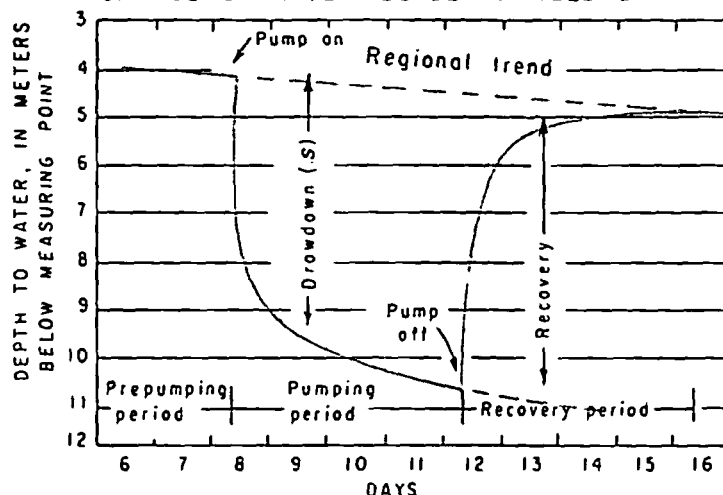
AQUIFER TESTS

MAP OF AQUIFER TEST SITE



(1)

CHANGE OF WATER LEVEL IN WELL B



(2)

Determining the yield of ground-water systems and evaluating the movement and fate of ground-water pollutants require, among other information, knowledge of:

1. The position and thickness of aquifers and confining beds.
2. The transmissivity and storage coefficient of the aquifers.
3. The hydraulic characteristics of the confining beds.
4. The position and nature of the aquifer boundaries.
5. The location and amounts of ground-water withdrawals.
6. The locations, kinds, and amounts of pollutants and pollutant practices.

Acquiring knowledge on these factors requires both geologic and hydrologic investigations. One of the most important hydrologic studies involves analyzing the change, with time, in water levels (or total heads) in an aquifer caused by withdrawals through wells. This type of study is referred to as an *aquifer test* and, in most cases, includes pumping a well at a constant rate for a period ranging from several hours to several days and measuring the change in water level in observation wells located at different distances from the pumped well (1).

Successful aquifer tests require, among other things:

1. Determination of the prepumping water-level trend (that is, the regional trend).
2. A carefully controlled constant pumping rate.
3. Accurate water-level measurements made at precisely known times during both the drawdown and the recovery periods.

Drawdown is the difference between the water level at any time during the test and the position at which the water level would have been if withdrawals had not started. Drawdown is very rapid at first. As pumping continues and the cone of depression expands, the rate of drawdown decreases (2).

The recovery of the water level under ideal conditions is a mirror image of the drawdown. The change in water level during the recovery period is the same as if withdrawals had continued at the same rate from the pumped well but, at the moment of pump cutoff, a recharge well had begun recharging water at the same point and at the same rate. Therefore, the recovery of the water level is the difference between the actual measured level and the projected pumping level (2).

In addition to the constant-rate aquifer test mentioned above, analytical methods have also been developed for several other types of aquifer tests. These methods include tests in which the rate of withdrawal is variable and tests that involve leakage of water across confining beds into confined aquifers. The analytical methods available also permit analysis of tests conducted on both vertical wells and horizontal wells or drains.

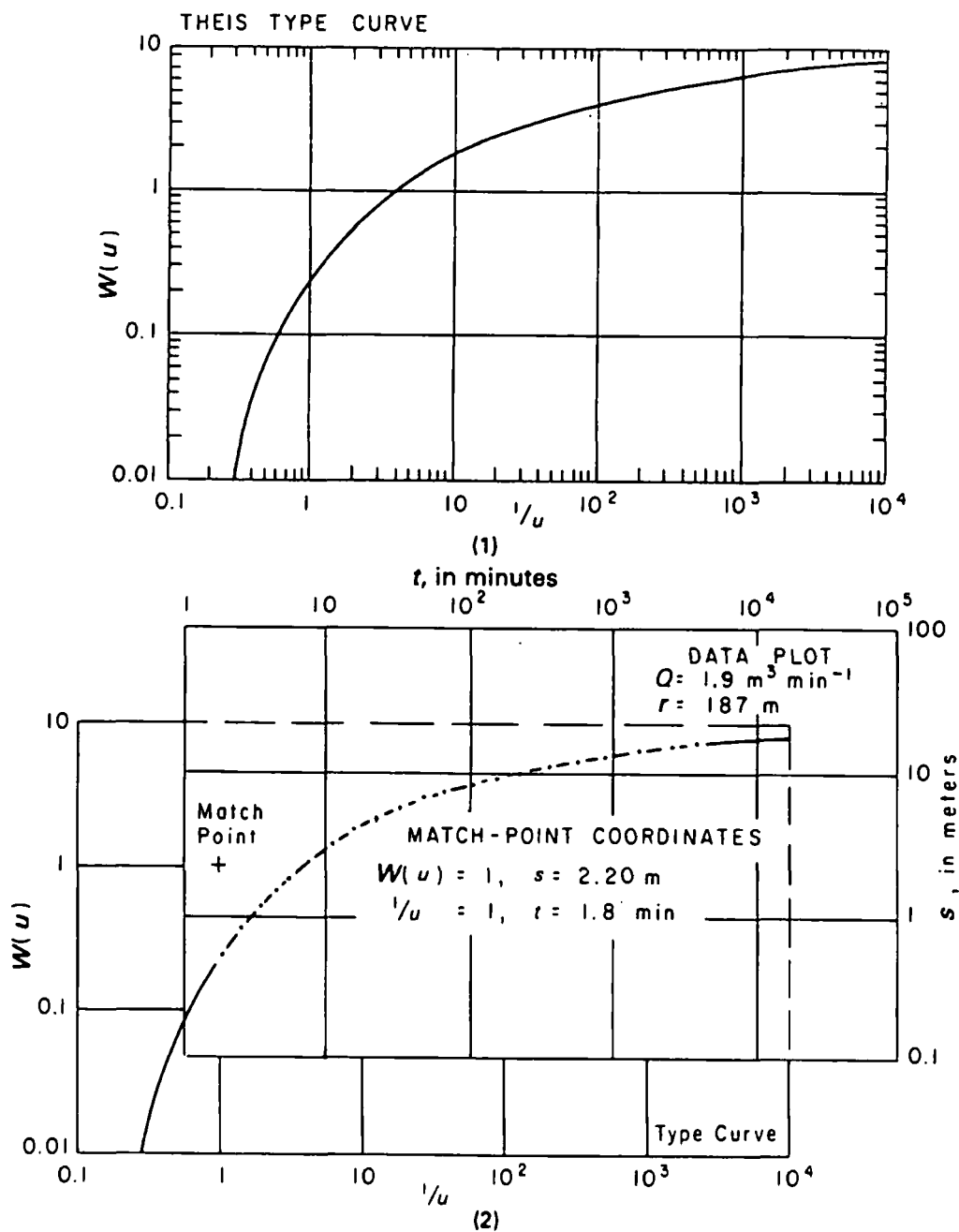
The most commonly used method of analysis of aquifer-test data—that for a vertical well pumped at a constant rate from an aquifer not affected by vertical leakage and lateral boundaries—will be covered in the discussion of "Analysis of Aquifer-Test Data." The method of analysis requires the use of a type curve based on the values of $W(u)$ and $1/u$ listed in the following table. Preparation and use of the type curve are covered in the following discussion.

SELECTED VALUES OF $W(u)$ FOR VALUES OF $1/u$

$1/u$	10	7.69	5.88	5.00	4.00	3.33	2.86	2.5	2.22	2.00	1.67	1.43	1.25	1.11
10^{-1}	0.219	0.135	0.075	0.049	0.025	0.013	0.007	0.004	0.002	0.001	0.000	0.000	0.000	0.000
1	1.82	1.59	1.36	1.22	1.04	.91	.79	.70	.63	.56	.45	.37	.31	.26
10	4.04	3.78	3.51	3.35	3.14	2.96	2.81	2.68	2.57	2.47	2.30	2.15	2.03	1.92
10^2	6.33	6.07	5.80	5.64	5.42	5.23	5.08	4.95	4.83	4.73	4.54	4.39	4.26	4.14
10^3	8.63	8.37	8.10	7.94	7.72	7.53	7.38	7.25	7.13	7.02	6.84	6.69	6.55	6.44
10^4	10.94	10.67	10.41	10.24	10.02	9.84	9.68	9.55	9.43	9.33	9.14	8.99	8.86	8.74
10^5	13.24	12.98	12.71	12.55	12.32	12.14	11.99	11.85	11.73	11.63	11.45	11.29	11.16	11.04
10^6	15.54	15.28	15.01	14.85	14.62	14.44	14.29	14.15	14.04	13.93	13.75	13.60	13.46	13.34
10^7	17.84	17.58	17.31	17.15	16.93	16.74	16.59	16.46	16.34	16.23	16.05	15.90	15.76	15.65
10^8	20.15	19.88	19.62	19.45	19.23	19.05	18.89	18.76	18.64	18.54	18.35	18.20	18.07	17.95
10^9	22.45	22.19	21.92	21.76	21.53	21.35	21.20	21.06	20.94	20.84	20.66	20.50	20.37	20.25
10^{10}	24.75	24.49	24.22	24.06	23.83	23.65	23.50	23.36	23.25	23.14	22.96	22.81	22.67	22.55
10^{11}	27.05	26.79	26.52	26.36	26.14	25.96	25.80	25.67	25.55	25.44	25.26	25.11	24.97	24.86
10^{12}	29.36	29.09	28.83	28.66	28.44	28.26	28.10	27.97	27.85	27.75	27.56	27.41	27.28	27.16
10^{13}	31.66	31.40	31.13	30.97	30.74	30.56	30.41	30.27	30.15	30.05	29.87	29.71	29.58	29.46
10^{14}	33.96	33.70	33.43	33.27	33.05	32.86	32.71	32.58	32.46	32.35	32.17	32.02	31.88	31.76

Examples: When $1/u = 10 \times 10^{-1}$, $W(u) = 0.219$; when $1/u = 3.33 \times 10^2$, $W(u) = 5.23$.

ANALYSIS OF AQUIFER-TEST DATA



In 1935, C. V. Theis of the New Mexico Water Resources District of the U.S. Geological Survey developed the first equation to include time of pumping as a factor that could be used to analyze the effect of withdrawals from a well. Thus, the *Theis equation* permitted, for the first time, determination of the hydraulic characteristics of an aquifer before the development of new steady-state conditions resulting from pumping. The importance of this capability may be realized from the fact that, under most conditions, a new steady state cannot be developed or that, if it can, many months or years may be required.

Theis assumed in the development of the equation that:

1. The transmissivity of the aquifer tapped by the pumping well is constant during the test to the limits of the cone of depression.
2. The water withdrawn from the aquifer is derived entirely from storage and is discharged instantaneously with the decline in head.
3. The discharging well penetrates the entire thickness of the aquifer, and its diameter is small in comparison with the pumping rate, so that storage in the well is negligible.

These assumptions are most nearly met by confined aquifers at sites remote from their boundaries. However, if certain precautions are observed, the equation can also be used to analyze tests of unconfined aquifers.

The forms of the Theis equation used to determine the transmissivity and storage coefficient are

$$T = \frac{Q W(u)}{4\pi s} \quad (1)$$

$$S = \frac{4Ttu}{r^2} \quad (2)$$

where T is transmissivity, S is the storage coefficient, Q is the pumping rate, s is drawdown, t is time, r is the distance from the pumping well to the observation well, $W(u)$ is the well function of u , which equals

$$-0.577216 - \log_e u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \dots$$

and $u = (r^2 S)/(4Tt)$.

The form of the Theis equation is such that it cannot be solved directly. To overcome this problem, Theis devised a convenient graphic method of solution that involves the use of a type curve (1). To apply this method, a data plot of drawdown versus time (or drawdown versus t/r^2) is matched to the type curve of $W(u)$ versus $1/u$ (2). At some convenient point on the overlapping part of the sheets containing the data plot and type curve, values of s , t (or t/r^2), $W(u)$, and $1/u$ are noted (2). These values are then substituted in equations 1 and 2, which are solved for T and S , respectively.

A Theis type curve of $W(u)$ versus $1/u$ can be prepared from the values given in the table contained in the preceding section, "Aquifer Tests." The data points are plotted on logarithmic graph paper—that is, graph paper having logarithmic divisions in both the x and y directions.

The dimensional units of transmissivity (T) are $L^2 t^{-1}$, where L is length and t is time in days. Thus, if Q in equation 1 is in cubic meters per day and s is in meters, T will be in square meters per day. Similarly, if, in equation 2, T is in square meters per day, t is in days, and r is in meters, S will be dimensionless.

Traditionally, in the United States, T has been expressed in units of gallons per day per foot. The common practice now is to report transmissivity in units of square meters per day or square feet per day. If Q is measured in gallons per minute, as is still normally the case, and drawdown is measured in feet, as is also normally the case, equation 1 is modified to obtain T in square feet per day as follows:

$$T = \frac{Q W(u)}{4\pi s} = \frac{\text{gal}}{\text{min}} \times \frac{1,440 \text{ min}}{\text{d}} \times \frac{\text{ft}^3}{7.48 \text{ gal}} \times \frac{1}{\text{ft}} \times \frac{W(u)}{4\pi}$$

or

$$T(\text{in ft}^2 \text{ d}^{-1}) = \frac{15.3Q W(u)}{s}$$

(when Q is in gallons per minute and s is in feet). To convert square feet per day to square meters per day, divide by 10.76.

The storage coefficient is dimensionless. Therefore, if T is in square feet per day, t is in minutes, and r is in feet, then, by equation 2,

$$S = \frac{4Ttu}{r^2} = \frac{4}{1} \times \frac{\text{ft}^2}{\text{d}} \times \frac{\text{min}}{\text{ft}^2} \times \frac{\text{d}}{1,440 \text{ min}}$$

or

$$S = \frac{Ttu}{360 r^2}$$

(when T is in square feet per day, t is in minutes, and r is in feet).

Analysis of aquifer-test data using the Theis equation involves plotting both the type curve and the test data on logarithmic graph paper. If the aquifer and the conditions of the test satisfy Theis's assumptions, the type curve has the same shape as the cone of depression along any line radiating away from the pumping well and the drawdown graph at any point in the cone of depression.

Use of the Theis equation for unconfined aquifers involves two considerations. First, if the aquifer is relatively fine grained, water is released slowly over a period of hours or days, not instantaneously with the decline in head. Therefore, the value of S determined from a short-period test may be too small.

Second, if the pumping rate is large and the observation well is near the pumping well, dewatering of the aquifer may be significant, and the assumption that the transmissivity of the aquifer is constant is not satisfied. The effect of dewatering of the aquifer can be eliminated with the following equation:

$$s' = s - \left(\frac{s^2}{2b} \right) \quad (3)$$

where s is the observed drawdown in the unconfined aquifer, b is the aquifer thickness, and s' is the drawdown that would have occurred if the aquifer had been confined (that is, if no dewatering had occurred).

To determine the transmissivity and storage coefficient of an unconfined aquifer, a data plot consisting of s' versus t (or t/r^2) is matched with the Theis type curve of $W(u)$ versus $1/u$. Both s and b in equation 3 must be in the same units, either feet or meters.

As noted above, Theis assumed in the development of his equation that the discharging well penetrates the entire thickness of the aquifer. However, because it is not always possible, or necessarily desirable, to design a well that fully penetrates the aquifer under development, most discharging wells are open to only a part of the aquifer that they draw from. Such partial penetration creates vertical flow in the vicinity of the discharging well that may affect drawdowns in observation wells located relatively close to the discharging well. Drawdowns in observation wells that are open to the same zone as the discharging well will be larger than the drawdowns in wells at the same distance from the discharging well but open to other zones. The possible effect of partial penetration on drawdowns must be considered in the analysis of aquifer-test data. If aquifer-boundary and other conditions permit, the problem can be avoided by locating observation wells beyond the zone in which vertical flow exists.

TIME-DRAWDOWN ANALYSIS

The Theis equation is only one of several methods that have been developed for the analysis of aquifer-test data. (See "Analysis of Aquifer-Test Data.") Another method, and one that is somewhat more convenient to use, was developed by C. E. Jacob from the Theis equation. The greater convenience of the Jacob method derives partly from its use of semilogarithmic graph paper instead of the logarithmic paper used in the Theis method and from the fact that, under ideal conditions, the data plot along a straight line rather than along a curve.

However, it is essential to note that, whereas the Theis equation applies at all times and places (if the assumptions are met), Jacob's method applies only under certain additional conditions. These conditions must also be satisfied in order to obtain reliable answers.

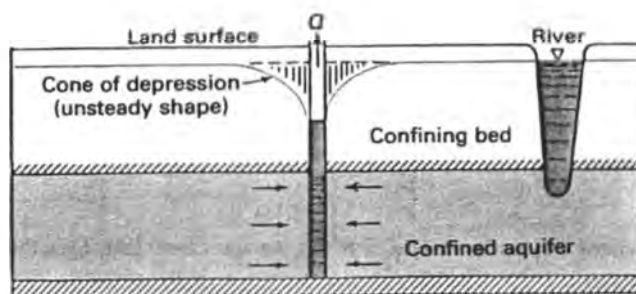
To understand the limitations of Jacob's method, we must consider the changes that occur in the cone of depression during an aquifer test. The changes that are of concern involve both the shape of the cone and the rate of drawdown. As the cone of depression migrates outward from a pumping well, its shape (and, therefore, the hydraulic gradient at different points in the cone) changes. We can refer to this condition as *unsteady shape*. At the start of withdrawals, the entire cone of depression has an unsteady shape (1). After a test has been underway for some time, the cone of depression begins to assume a relatively *steady shape*, first at the pumping well and then gradually to greater and greater distances (2). If withdrawals continue long enough for increases in recharge and (or) reductions in discharge to balance the rate of withdrawal, drawdowns cease, and the cone of depression is said to be in a *steady state* (3).

The Jacob method is applicable only to the zone in which steady-shape conditions prevail or to the entire cone only after steady-state conditions have developed. For practical purposes, this condition is met when $u = (r^2 S)/(4Tt)$ is equal to or less than about 0.05. Substituting this value in the equation for u and solving for t , we can determine the time at which steady-shape conditions develop at the outermost observation well. Thus,

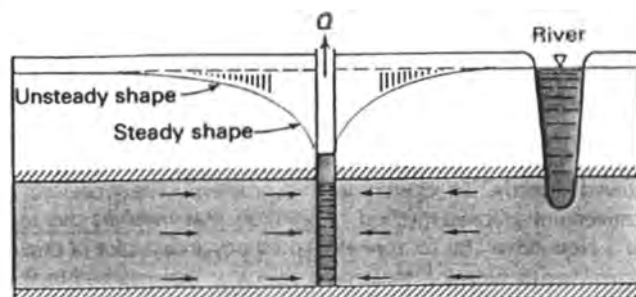
$$t_c = \frac{7,200 r^2 S}{T} \quad (1)$$

where t_c is the time, in minutes, at which steady-shape conditions develop, r is the distance from the pumping well, in feet (or meters), S is the estimated storage coefficient (dimensionless), and T is the estimated transmissivity, in square feet per day (or square meters per day).

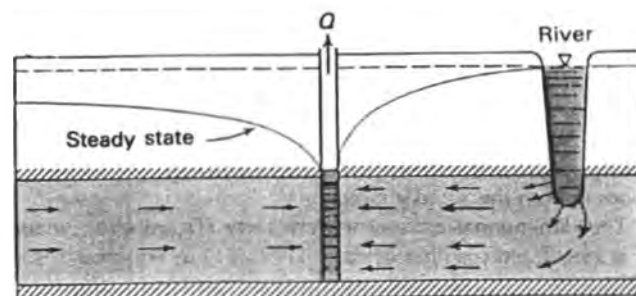
After steady-shape conditions have developed, the drawdowns at an observation well begin to fall along a straight line on semilogarithmic graph paper, as sketch 4 shows. Before that time, the drawdowns plot below the extension of the straight line. When a time-drawdown graph is prepared, drawdowns are plotted on the vertical (arithmetic) axis versus time on the horizontal (logarithmic) axis.



(1)



(2)



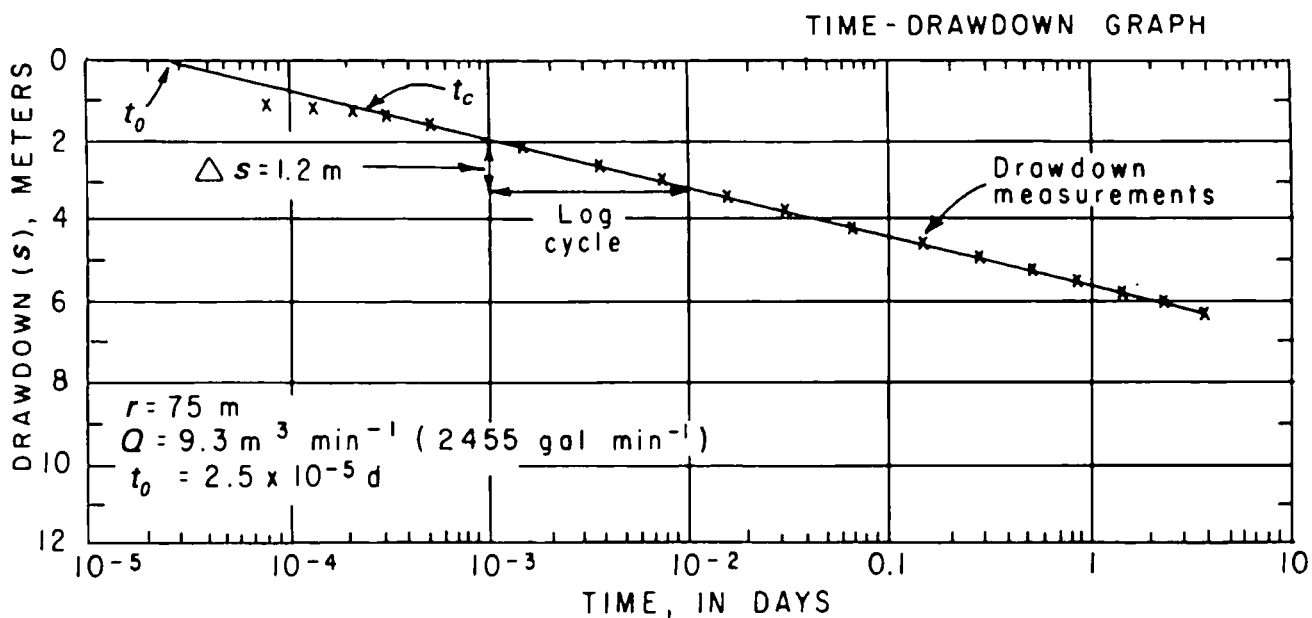
(3)

The slope of the straight line is proportional to the pumping rate and to the transmissivity. Jacob derived the following equations for determination of transmissivity and storage coefficient from the time-drawdown graphs:

$$T = \frac{2.3 Q}{4\pi \Delta s} \quad (2)$$

$$S = \frac{2.25 T t_0}{r^2} \quad (3)$$

where Q is the pumping rate, Δs is the drawdown across one log cycle, t_0 is the time at the point where the straight line intersects the zero-drawdown line, and r is the distance from the pumping well to the observation well.



(4)

Equations 2 and 3 are in consistent units. Thus, if Q is in cubic meters per day and s is in meters, T is in square meters per day. S is dimensionless, so that, in equation 3, if T is in square meters per day, then r must be in meters and t_0 must be in days.

It is still common practice in the United States to express Q in gallons per minute, s in feet, t in minutes, r in feet, and T in square feet per day. We can modify equations 2 and 3 for direct substitution of these units as follows:

$$T = \frac{35 Q}{\Delta s} \quad (4)$$

(where T is in square feet per day, Q is in gallons per minute, and Δs is in feet) and

$$S = \frac{2.25 T t_0}{r^2} = \frac{2.25}{1} \times \frac{\text{ft}^2}{\text{d}} \times \frac{\text{min}}{\text{ft}^2} \times \frac{\text{d}}{1,440 \text{ min}}$$

$$S = \frac{T t_0}{640 r^2} \quad (5)$$

$$T = \frac{2.3 Q}{4\pi \Delta s} = \frac{2.3}{4\pi} \times \frac{\text{gal}}{\text{min}} \times \frac{1,440 \text{ min}}{\text{d}} \times \frac{\text{ft}^3}{7.48 \text{ gal}} \times \frac{1}{\text{ft}}$$

(where T is in square feet per day, t_0 is in minutes, and r is in feet).

DISTANCE-DRAWDOWN ANALYSIS

It is desirable in aquifer tests to have at least three observation wells located at different distances from the pumping well (1). Drawdowns measured at the same time in these wells can be analyzed with the Theis equation and type curve to determine the aquifer transmissivity and storage coefficient.

After the test has been underway long enough, drawdowns in the wells can also be analyzed by the Jacob method, either through the use of a time-drawdown graph using data from individual wells or through the use of a distance-drawdown graph using "simultaneous" measurements in all of the wells. To determine when sufficient time has elapsed, see "Time-Drawdown Analysis."

In the Jacob distance-drawdown method, drawdowns are plotted on the vertical (arithmetic) axis versus distance on the horizontal (logarithmic) axis (2). If the aquifer and test conditions satisfy the Theis assumptions and the limitation of the Jacob method, the drawdowns measured at the same time in different wells should plot along a straight line (2).

The slope of the straight line is proportional to the pumping rate and to the transmissivity. Jacob derived the following equations for determination of the transmissivity and storage coefficient from distance-drawdown graphs:

$$T = \frac{2.3Q}{2\pi\Delta s} \quad (1)$$

$$S = \frac{2.25Tt}{r_o^2} \quad (2)$$

where Q is the pumping rate, Δs is the drawdown across one log cycle, t is the time at which the drawdowns were measured, and r_o is the distance from the pumping well to the point where the straight line intersects the zero-drawdown line.

Equations 1 and 2 are in consistent units. For the inconsistent units still in relatively common use in the United States, equations 1 and 2 should be used in the following forms:

$$T = \frac{70 Q}{\Delta s} \quad (3)$$

(where T is in square feet per day, Q is in gallons per minute, and Δs is in feet) and

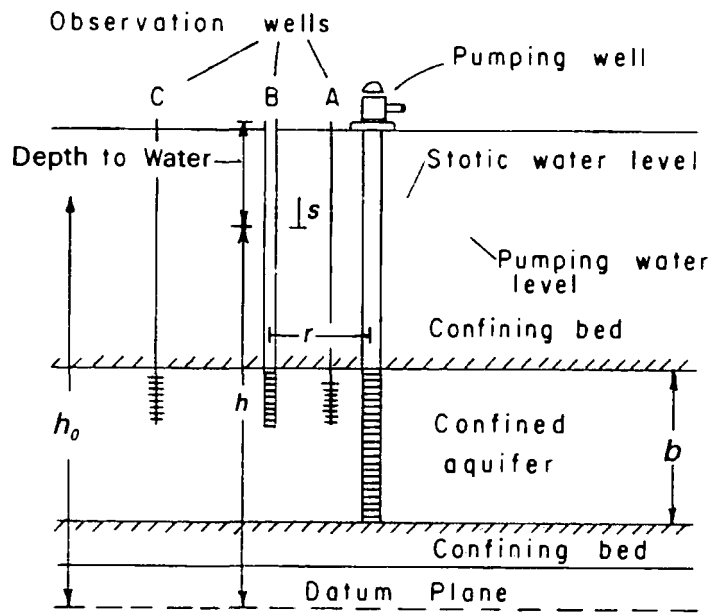
$$S = \frac{Tt}{640 r_o^2} \quad (4)$$

(where T is in square feet per day, t is in minutes, and r_o is in feet).

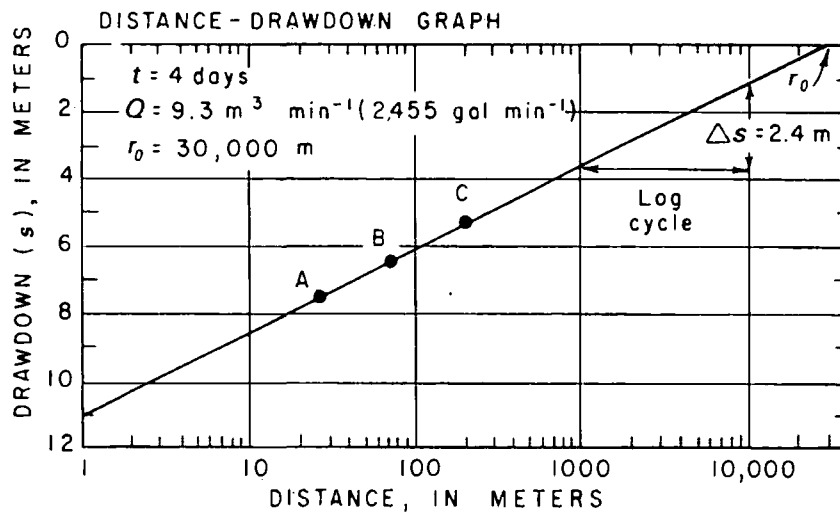
The distance r_o does not indicate the outer limit of the cone of depression. Because nonsteady-state conditions exist in the outer part of the cone, before the development of steady-state conditions, the Jacob method does not apply to that part. If the Theis equation were used to calculate drawdowns in the outer part of the cone, it would be found that they would plot below the straight line. In other words, the measurable limit of the cone of depression is beyond the distance r_o .

If the straight line of the distance-drawdown graph is extended inward to the radius of the pumping well, the drawdown indicated at that point is the drawdown in the aquifer outside of the well. If the drawdown inside the well is found to be greater than the drawdown outside, the difference is attributable to well loss. (See "Single-Well Tests.")

As noted in the section on "Hydraulic Conductivity," the hydraulic conductivities and, therefore, the transmissivities of aquifers may be different in different directions. These differences may cause drawdowns measured at the same time in observation wells located at the same distances but in different directions from the discharging well to be different. Where this condition exists, the distance-drawdown method may yield satisfactory results only where three or more observation wells are located in the same direction but at different distances from the discharging well.

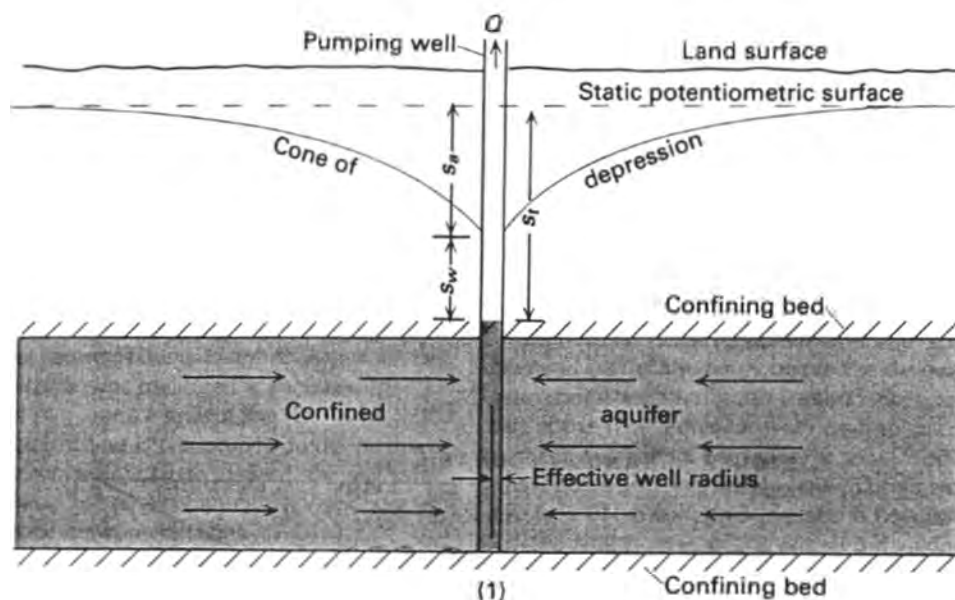


(1)



(2)

SINGLE-WELL TESTS



The most useful aquifer tests are those that include water-level measurements in observation wells. Such tests are commonly referred to as *multiple-well tests*. It is also possible to obtain useful data from production wells, even where observation wells are not available. Such tests are referred to as *single-well tests* and may consist of pumping a well at a single constant rate, or at two or more different but constant rates (see "Well-Acceptance Tests and Well Efficiency") or, if the well is not equipped with a pump, by "instantaneously" introducing a known volume of water into the well. This discussion will be limited to tests involving a single constant rate.

In order to analyze the data, it is necessary to understand the nature of the drawdown in a pumping well. The total drawdown (s_t) in most, if not all, pumping wells consists of two components (1). One is the drawdown (s_a) in the aquifer, and the other is the drawdown (s_w) that occurs as water moves from the aquifer into the well and up the well bore to the pump intake. Thus, the drawdown in most pumping wells is greater than the drawdown in the aquifer at the radius of the pumping well.

The total drawdown (s_t) in a pumping well can be expressed in the form of the following equations:

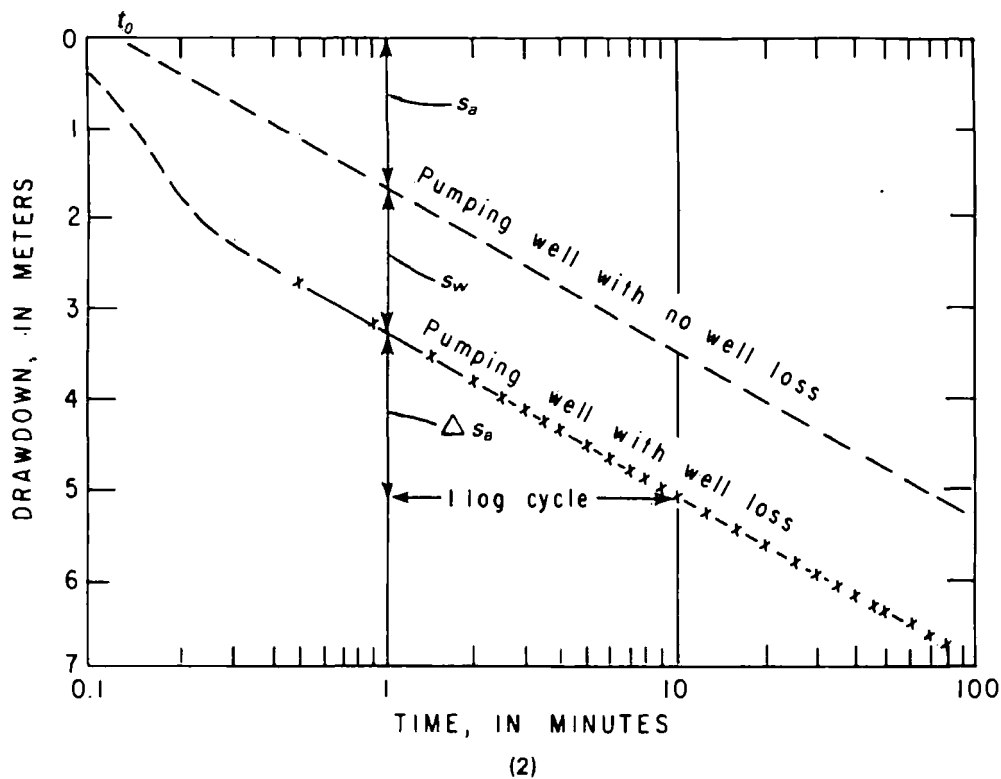
$$\begin{aligned} s_t &= s_a + s_w \\ s_t &= BQ + CQ^2 \end{aligned} \quad (1)$$

where s_a is the drawdown in the aquifer at the effective radius of the pumping well, s_w is well loss, Q is the pumping rate, B is a factor related to the hydraulic characteristics of the aquifer and the length of the pumping period, and C is a factor related to the characteristics of the well.

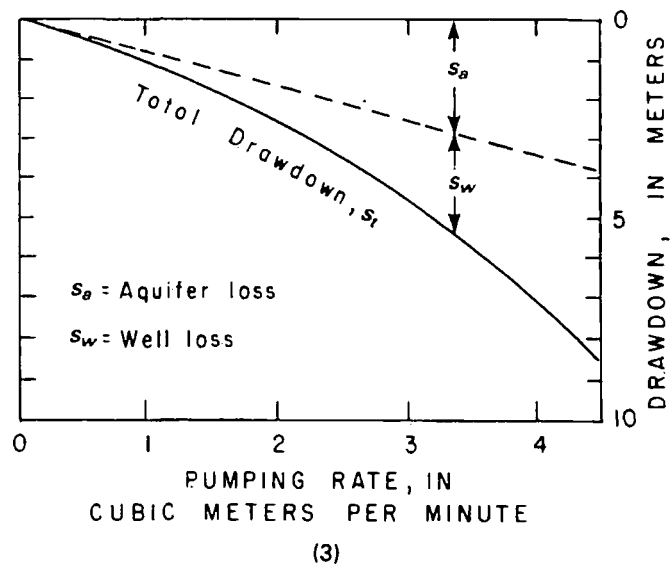
The factor C in equation 1 is normally considered to be constant, so that, in a constant rate test, CQ^2 is also constant. As a result, the well loss (s_w) increases the total drawdown in the pumping well but does not affect the rate of change in the drawdown with time. It is, therefore, possible to analyze drawdowns in the pumping well with the Jacob time-drawdown method using semilogarithmic graph paper. (See "Time-Drawdown Analysis.") Drawdowns are plotted on the arithmetic scale versus time on the logarithmic scale (2), and transmissivity is determined from the slope of the straight line through the use of the following equation:

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (2)$$

Where well loss is present in the pumping well, the storage coefficient cannot be determined by extending the straight line to the line of zero drawdown. Even where well loss is not present, the determination of the storage coefficient from drawdowns in a pumping well likely will be subject to large error because the effective radius of the well may differ significantly from the "nominal" radius.

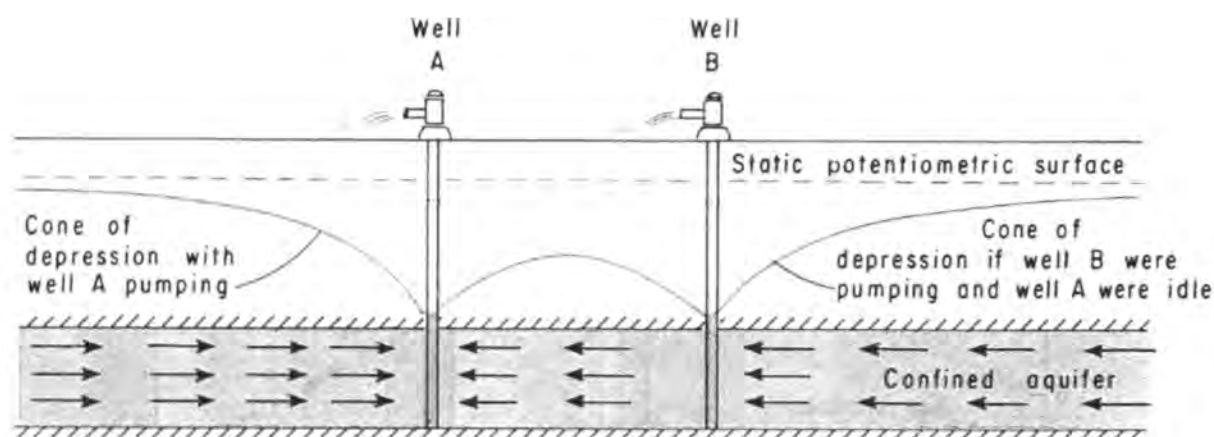


RELATION OF PUMPING RATE
AND DRAWDOWN

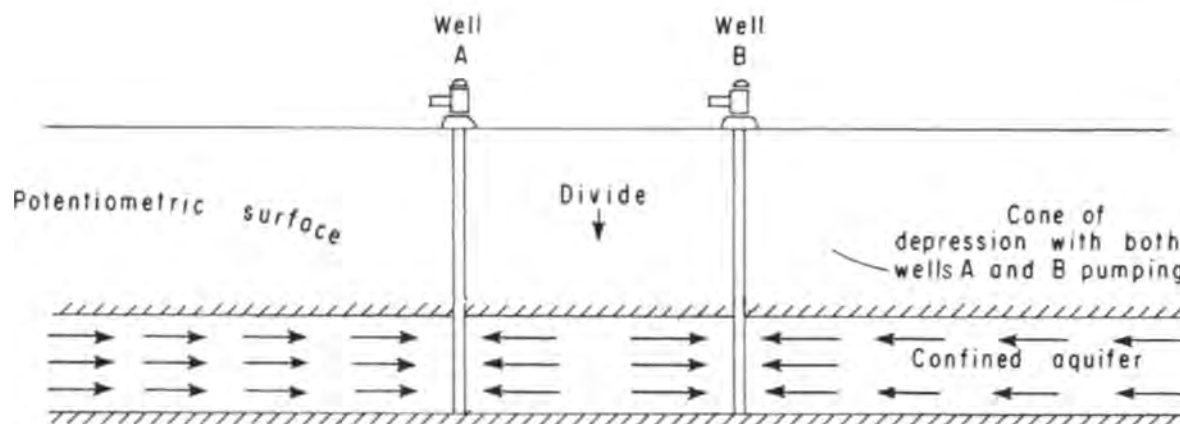


In equation 1, drawdown in the pumping well is proportional to the pumping rate. The factor B in the aquifer-loss term (BQ) increases with time of pumping as long as water is being derived from storage in the aquifer. The factor C in the well-loss term (CQ^2) is a constant if the characteristics of the well remain unchanged, but, because the pumping rate in the well-loss term is squared, drawdown due to well loss increases

rapidly as the pumping rate is increased. The relation between pumping rates and drawdown in a pumping well, if the well was pumped for the same length of time at each rate, is shown in sketch 3. The effect of well loss on drawdown in the pumping well is important both in the analysis of data from pumping wells and in the design of supply wells.



(1)



(2)

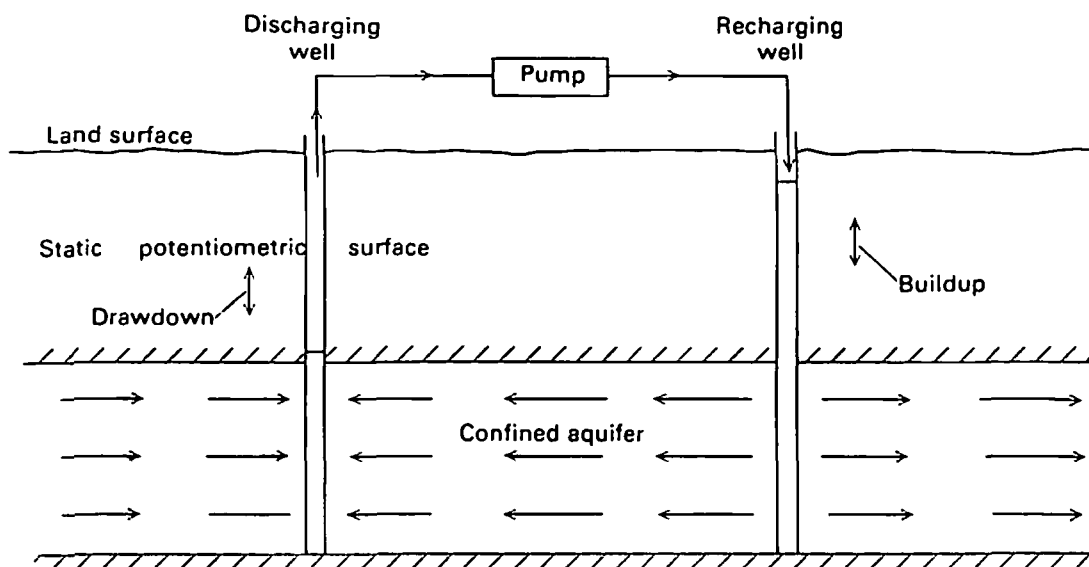
Pumping a well causes a drawdown in the ground-water level in the surrounding area. The drawdown in water level forms a conical-shaped depression in the water table or potentiometric surface, which is referred to as a *cone of depression*. (See "Cone of Depression.") Similarly, a well through which water is injected into an aquifer (that is, a recharge or injection well) causes a buildup in ground-water level in the form of a conical-shaped mound.

The drawdown (s) in an aquifer caused by pumping at any point in the aquifer is directly proportional to the pumping rate (Q) and the length of time (t) that pumping has been in progress and is inversely proportional to the transmissivity (T), the storage coefficient (S), and the square of the distance (r^2) between the pumping well and the point. In other words,

$$s \approx \frac{Q_s t}{T S r^2} \quad (1)$$

Where pumping wells are spaced relatively close together, pumping of one will cause a drawdown in the others. Drawdowns are additive, so that the total drawdown in a pumping well is equal to its own drawdown plus the drawdowns caused at its location by other pumping wells (1) (2). The drawdowns in pumping wells caused by withdrawals from other pumping wells are referred to as *well interference*. As sketch 2 shows, a divide forms in the potentiometric surface (or the water table, in the case of an unconfined aquifer) between pumping wells.

At any point in an aquifer affected by both a discharging well and a recharging well, the change in water level is equal to the difference between the drawdown and the buildup. If the rates of discharge and recharge are the same and if the wells are operated on the same schedule, the drawdown and the buildup will cancel midway between the wells, and the water level at that point will remain unchanged from the static level (3). (See "Aquifer Boundaries.")



(3)

We see from the above functional equation that, in the absence of well interference, drawdown in an aquifer at the effective radius of a pumping well is directly proportional to the pumping rate. Conversely, the maximum pumping rate is directly proportional to the *available drawdown*. For confined aquifers, available drawdown is normally considered to be the distance between the prepumping water level and the top of the aquifer. For unconfined aquifers, available drawdown is normally considered to be about 60 percent of the saturated aquifer thickness.

Where the pumping rate of a well is such that only a part of the available drawdown is utilized, the only effect of well interference is to lower the pumping level and, thereby, increase pumping costs. In the design of a well field, the increase in pumping cost must be evaluated along with the cost

of the additional waterlines and powerlines that must be installed if the spacing of wells is increased to reduce well interference. (See "Well-Field Design.")

Because well interference reduces the available drawdown, it also reduces the maximum yield of a well. Well interference is, therefore, an important matter in the design of well fields where it is desirable for each well to be pumped at the largest possible rate. We can see from equation 1 that, for a group of wells pumped at the same rate and on the same schedule, the well interference caused by any well on another well in the group is inversely proportional to the square of the distance between the two wells (r^2). Therefore, excessive well interference is avoided by increasing the spacing between wells and by locating the wells along a line rather than in a circle or in a grid pattern.

AQUIFER BOUNDARIES

One of the assumptions inherent in the Theis equation (and in most other fundamental ground-water flow equations) is that the aquifer to which it is being applied is infinite in extent. Obviously, no such aquifer exists on Earth. However, many aquifers are areally extensive, and, because pumping will not affect recharge or discharge significantly for many years, most water pumped is from ground-water storage; as a consequence, water levels must decline for many years. An excellent example of such an aquifer is that underlying the High Plains from Texas to South Dakota.

All aquifers are bounded in both the vertical direction and the horizontal direction. For example, vertical boundaries may include the water table, the plane of contact between each aquifer and each confining bed, and the plane marking the lower limit of the zone of interconnected openings—in other words, the base of the ground-water system.

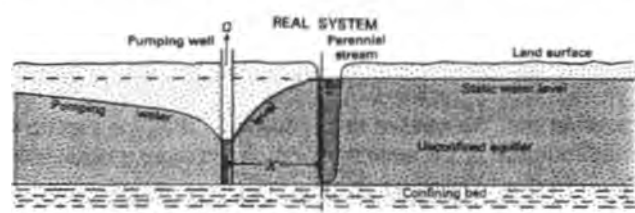
Hydraulically, aquifer boundaries are of two types: recharge boundaries and impermeable boundaries. A *recharge boundary* is a boundary along which flow lines originate. In other words, such a boundary will, under certain hydraulic

conditions, serve as a source of recharge to the aquifer. Examples of recharge boundaries include the zones of contact between an aquifer and a perennial stream that completely penetrates the aquifer or the ocean.

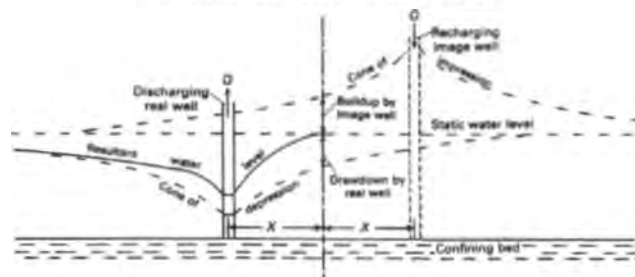
An *impermeable boundary* is a boundary that flow lines do not cross. Such boundaries exist where aquifers terminate against "impermeable" material. Examples include the contact between an aquifer composed of sand and a laterally adjacent bed composed of clay.

The position and nature of aquifer boundaries are of critical importance in many ground-water problems, including the movement and fate of pollutants and the response of aquifers to withdrawals. Depending on the direction of the hydraulic gradient, a stream, for example, may be either the source or the destination of a pollutant.

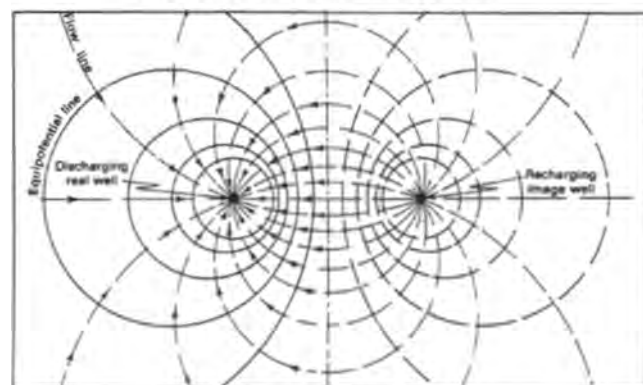
Lateral boundaries within the cone of depression have a profound effect on the response of an aquifer to withdrawals. To analyze, or to predict, the effect of a lateral boundary, it is necessary to "make" the aquifer appear to be of infinite extent. This feat is accomplished through the use of imaginary



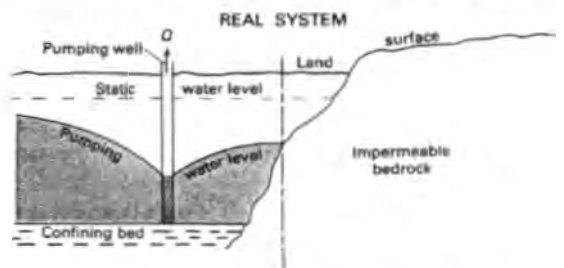
HYDRAULIC COUNTERPART OF REAL SYSTEM



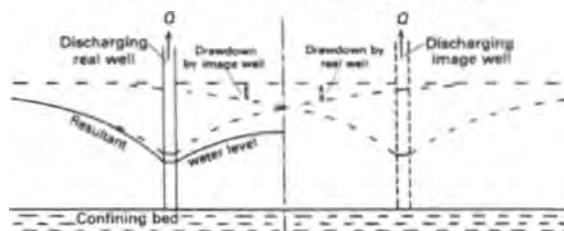
PLAN VIEW OF THE HYDRAULIC COUNTERPART



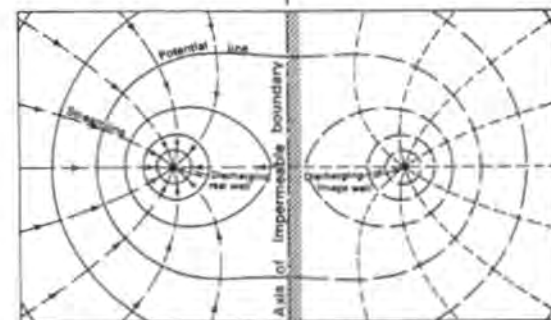
(1)



HYDRAULIC COUNTERPART OF REAL SYSTEM



PLAN VIEW OF THE HYDRAULIC COUNTERPART



(2)

wells and the theory of images. Sketches 1 and 2 show, in both plan view and profile, how image wells are used to compensate, hydraulically, for the effects of both recharging and impermeable boundaries. (See "Well Interference.")

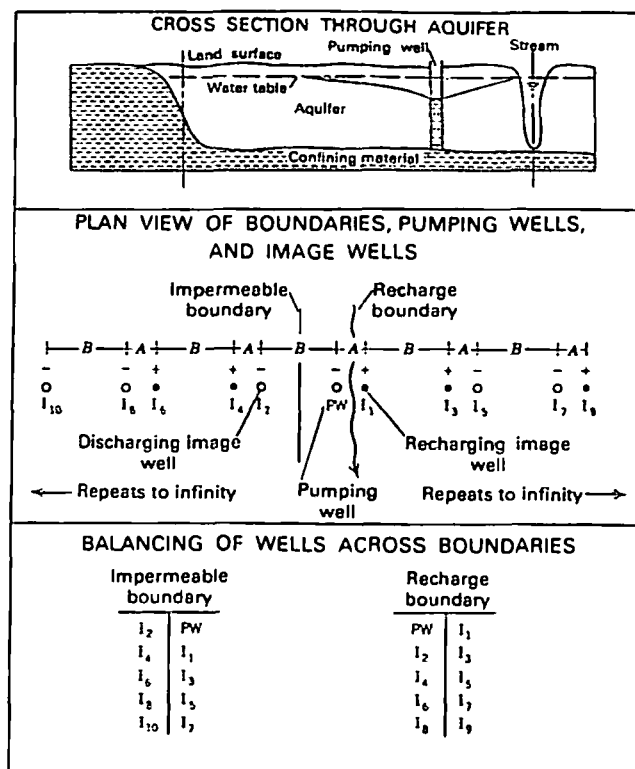
The key feature of a recharge boundary is that withdrawals from the aquifer do not produce drawdowns across the boundary. A perennial stream in intimate contact with an aquifer represents a recharge boundary because pumping from the aquifer will induce recharge from the stream. The hydraulic effect of a recharge boundary can be duplicated by assuming that a recharging image well is present on the side of the boundary opposite the real discharging well. Water is injected into the image well at the same rate and on the same schedule that water is withdrawn from the real well. In the plan view in sketch 1, flow lines originate at the boundary, and equipotential lines parallel the boundary at the closest point to the pumping (real) well.

The key feature of an impermeable boundary is that no water can cross it. Such a boundary, sometimes termed a "no-flow boundary," resembles a divide in the water table or the potentiometric surface of a confined aquifer. The effect of an impermeable boundary can be duplicated by assuming that a discharging image well is present on the side of the boundary opposite the real discharging well. The image well withdraws water at the same rate and on the same schedule as the real well. Flow lines tend to be parallel to an impermeable boundary, and equipotential lines intersect it at a right angle.

The image-well theory is an essential tool in the design of well fields near aquifer boundaries. Thus, on the basis of minimizing the lowering of water levels, the following conditions apply:

1. Pumping wells should be located parallel to and as close as possible to recharging boundaries.
2. Pumping wells should be located perpendicular to and as far as possible from impermeable boundaries.

Sketches 1 and 2 illustrate the effect of single boundaries and show how their hydraulic effect is compensated for through the use of single image wells. It is assumed in these sketches that other boundaries are so remote that they have a negligible effect on the areas depicted. At many places, however, pumping wells are affected by two or more boundaries. One example is an alluvial aquifer composed of sand

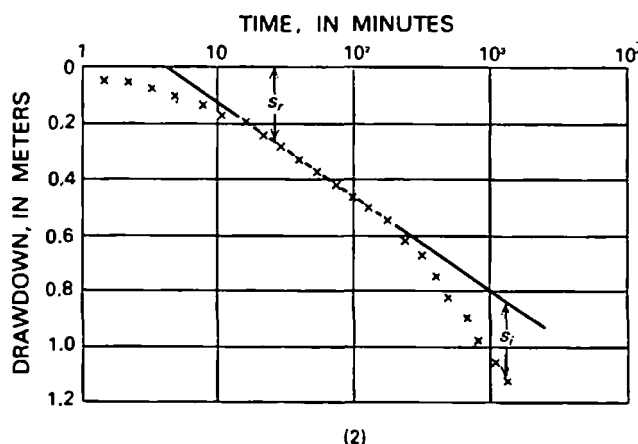
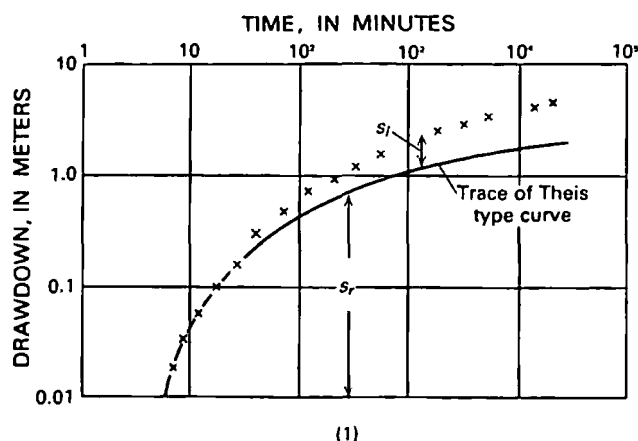


(3)

and gravel bordered on one side by a perennial stream (a recharge boundary) and on the other by impermeable bedrock (an impermeable boundary).

Contrary to first impression, these boundary conditions cannot be satisfied with only a recharging image well and a discharging image well. Additional image wells are required, as sketch 3 shows, to compensate for the effect of the image wells on the opposite boundaries. Because each new image well added to the array affects the opposite boundary, it is necessary to continue adding image wells until their distances from the boundaries are so great that their effect becomes negligible.

TESTS AFFECTED BY LATERAL BOUNDARIES

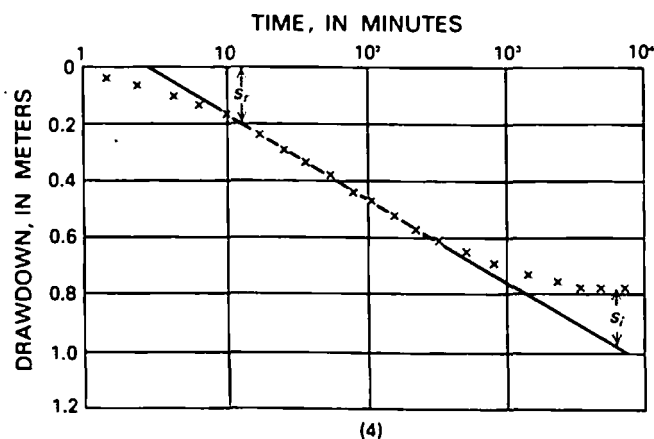
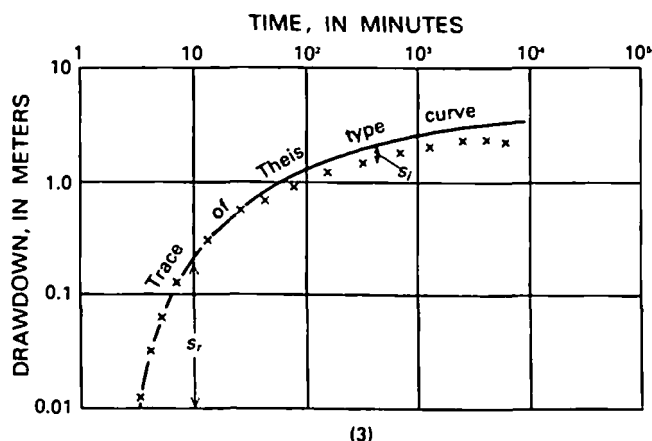


When an aquifer test is conducted near one of the lateral boundaries of an aquifer, the drawdown data depart from the Theis type curve and from the initial straight line produced by the Jacob method. The hydraulic effect of lateral boundaries is assumed, for analytical convenience, to be due to the presence of other wells. (See "Aquifer Boundaries.") Thus, a recharge boundary has the same effect on drawdowns as a recharging image well located across the boundary and at the same distance from the boundary as the real well. The image well is assumed to operate on the same schedule and at the same rate as the real well. Similarly, an impermeable boundary has the same effect on drawdowns as a discharging image well.

To analyze aquifer-test data affected by either a recharge boundary or an impermeable boundary, the early drawdown data in the observation wells nearest the pumping well must not be affected by the boundary. These data, then, show only the effect of the real well and can be used to determine the transmissivity (T) and the storage coefficient (S) of the aquifer. (See "Analysis of Aquifer-Test Data" and "Time-Drawdown Analysis.") In the Theis method, the type curve is matched to

the early data, and a "match point" is selected for use in calculating values of T and S . The position of the type curve, in the region where the drawdowns depart from the type curve, is traced onto the data plot (1) (3). The trace of the type curve shows where the drawdowns would have plotted if there had been no boundary effect. The differences in drawdown between the data plot and the trace of the type curve show the effect of an aquifer boundary. The direction in which the drawdowns depart from the type curve—that is, in the direction of either greater drawdowns or lesser drawdowns—shows the type of boundary.

Drawdowns greater than those defined by the trace of the type curve indicate the presence of an impermeable boundary because, as noted above, the effect of such boundaries can be duplicated with an imaginary discharging well (1). Conversely, a recharge boundary causes drawdowns to be less than those defined by the trace of the type curve (3).



In the Jacob method, drawdowns begin to plot along a straight line after the test has been underway for some time (2) (4). The time at which the straight-line plot begins depends on the values of T and S of the aquifer and on the square of the

distance between the observation well and the pumping well. (See "Time-Drawdown Analysis.") Values of T and S are determined from the first straight-line segment defined by the drawdowns after the start of the aquifer test. The slope of this straight line depends on the transmissivity (T) and on the pumping rate (Q). If a boundary is present, the drawdowns will depart from the first straight-line segment and begin to fall along another straight line (2) (4).

According to image-well theory, the effect of a recharge boundary can be duplicated by assuming that water is injected into the aquifer through a recharging image well at the same rate that water is being withdrawn from the real well. It follows, therefore, that, when the full effect of a recharge boundary is felt at an observation well, there will be no further increase in drawdown, and the water level in the well will stabilize. At this point in both the Theis and the Jacob methods, drawdowns plot along a straight line having a constant drawdown (3) (4). Conversely, an impermeable boundary causes the rate of drawdown to increase. In the Jacob method, as a result, the drawdowns plot along a new straight line having twice the slope as the line drawn through the drawdowns that occurred before the effect of the boundary was felt (2).

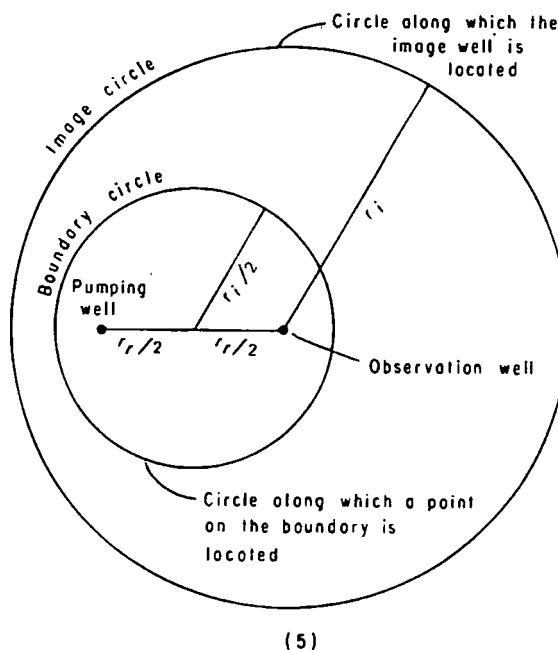
A word of caution should be injected here regarding use of the Jacob method when it is suspected that an aquifer test may be affected by boundary conditions. In many cases, the boundary begins to affect drawdowns before the method is applicable, the result being that T and S values determined from the data are erroneous, and the effect of the boundary is not identified. When it is suspected that an aquifer test may be affected by boundary conditions, the data should, at least initially, be analyzed with the Theis method.

The position and the nature of many boundaries are obvious. For example, the most common recharge boundaries are streams and lakes; possibly, the most common impermeable boundaries are the bedrock walls of alluvial valleys. The hydraulic distance to these boundaries, however, may not be obvious. A stream or lake may penetrate only a short distance into an aquifer, and their bottoms may be underlain by fine-grained material that hampers movement of water into the aquifer. Hydraulically, the boundaries formed by these surface-water bodies will appear to be farther from the pumping well than the near shore. Similarly, if a small amount of water moves across the bedrock wall of a valley, the hydraulic distance to the impermeable boundary will be greater than the distance to the valley wall.

Fortunately, the hydraulic distance to boundaries can be determined from the analysis of aquifer-test data. According to the Theis equation, if we deal with equal drawdowns caused by the real well and the image well (in other words, if $s_r = s_i$), then

$$\frac{r_r^2}{t_r} = \frac{r_i^2}{t_i} \quad (1)$$

where r_r is the distance from the observation well to the real well, r_i is the distance from the observation well to the image well, t_r is the time at which a drawdown of s_r is caused by the real well at the observation well, and t_i is the time at which a drawdown of s_i is caused by the image well at the observation well.



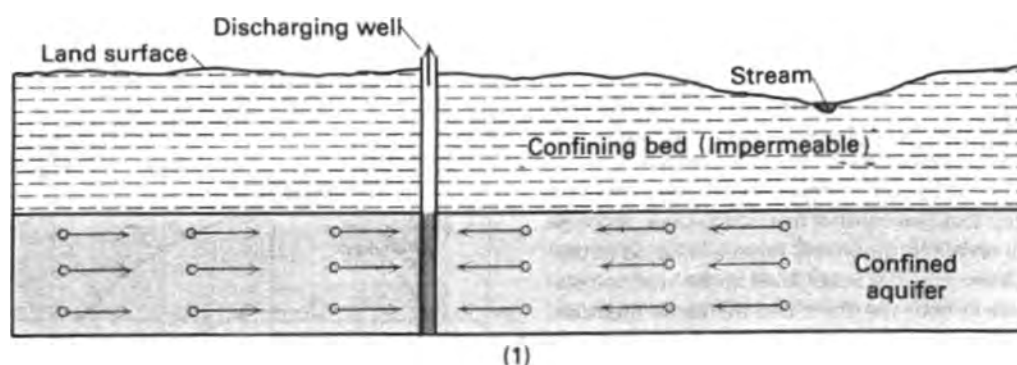
Solving equation 1 for the distance to the image well from the observation well, we obtain

$$r_i = r_r \sqrt{\frac{t_i}{t_r}} \quad (2)$$

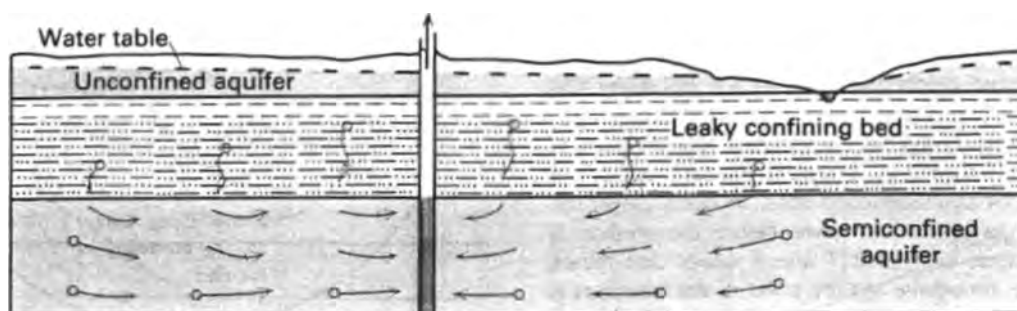
The image well is located at some point on a circle having a radius of r_i centered on the observation well (5). Because the image well is the same distance from the boundary as the real well, we know the boundary is halfway between the image well and the pumping well (5).

If the boundary is a stream or valley wall or some other feature whose physical position is obvious, its "hydraulic position" may be determined by using data from a single observation well. If, on the other hand, the boundary is the wall of a buried valley or some other feature not obvious from the land surface, distances to the image well from three observation wells may be needed to identify the position of the boundary.

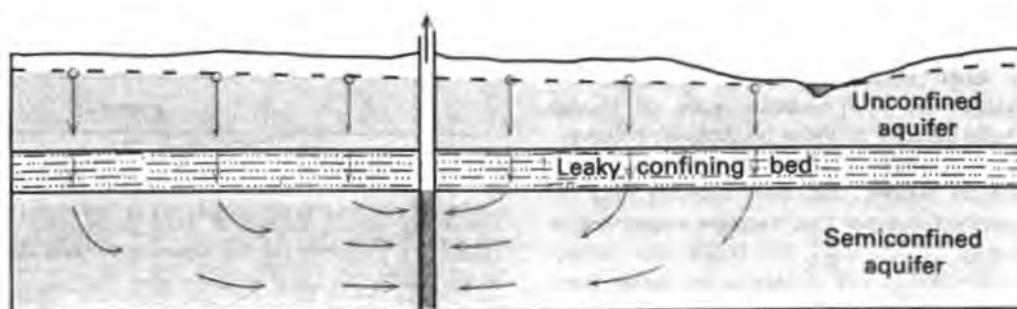
TESTS AFFECTED BY LEAKY CONFINING BEDS



(1)



(2)



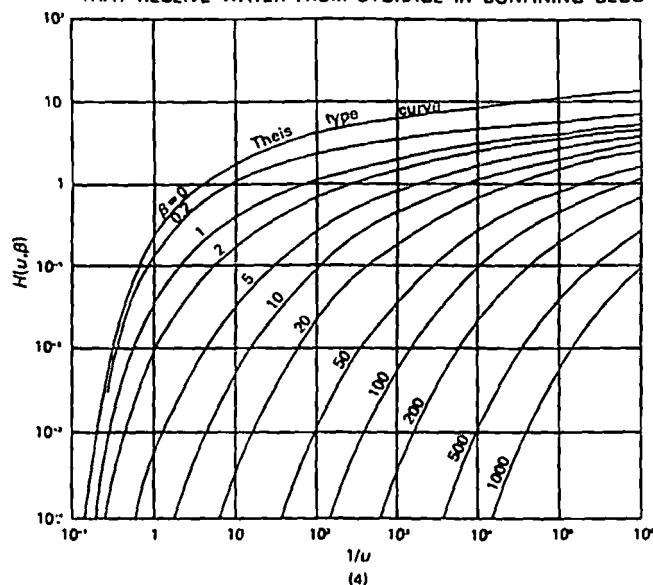
(3)

In the development of the Theis equation for the analysis of aquifer-test data, it was assumed that all water discharged from the pumping well was derived instantaneously from storage in the aquifer. (See "Analysis of Aquifer-Test Data.") Therefore, in the case of a confined aquifer, at least during the period of the test, the movement of water into the aquifer across its overlying and underlying confining beds is negligible. This assumption is satisfied by many confined aquifers. Many other aquifers, however, are bounded by leaky confining beds that transmit water into the aquifer in response to the withdrawals and cause drawdowns to differ from those that would be predicted by the Theis equation. The analysis of aquifer tests conducted on these aquifers requires the use of the methods that have been developed for semiconfined

aquifers (also referred to in ground-water literature as "leaky aquifers").

Sketches 1 through 3 illustrate three different conditions commonly encountered in the field. Sketch 1 shows a confined aquifer bounded by thick, impermeable confining beds. Water initially pumped from such an aquifer is from storage, and aquifer-test data can be analyzed by using the Theis equation. Sketch 2 shows an aquifer overlain by a thick, leaky confining bed that, during an aquifer test, yields significant water from storage. The aquifer in this case may properly be referred to as a semiconfined aquifer, and the release of water from storage in the confining bed affects the analysis of aquifer-test data. Sketch 3 shows an aquifer overlain by a thin confining bed that does not yield significant water from storage but that

HANTUSH TYPE CURVES FOR SEMICONFINED AQUIFERS THAT RECEIVE WATER FROM STORAGE IN CONFINING BEDS



is sufficiently permeable to transmit water from the overlying unconfined aquifer into the semiconfinied aquifer. Methods have been devised, largely by Madhi Hantush and C. E. Jacob, for use in analyzing the leaky conditions illustrated in sketches 2 and 3.

The use of these methods involves matching data plots with type curves, as the Theis method does. The major difference is that, whereas the Theis method involves use of a single type curve, the methods applicable to semiconfinied aquifers involve "families" of type curves, each curve of which reflects different combinations of the hydraulic characteristics of the aquifer and the confining beds. Data plots of s versus t on logarithmic graph paper for aquifer tests affected by release of water from storage in the confining beds are matched to the family of type curves illustrated in sketch 4. For convenience, these curves are referred to as Hantush type. Four match-point coordinates are selected and substituted into the following equations to determine values of T and S :

$$T = \frac{QH(u, \beta)}{4\pi s} \quad (1)$$

$$S = \frac{4Ttu}{r^2} \quad (2)$$

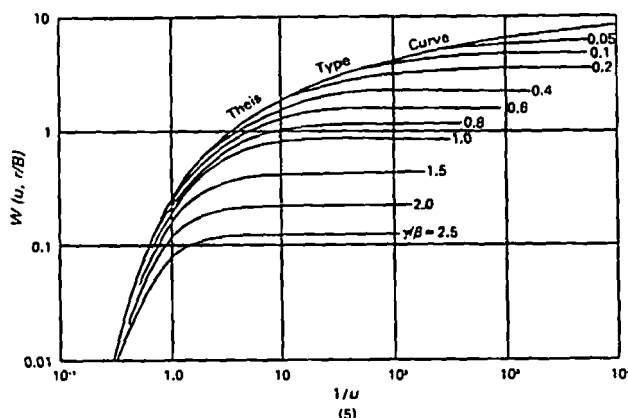
Data plots of s versus t on logarithmic graph paper for aquifer tests affected by leakage of water across confining

beds are matched to the family of type curves shown in sketch 5. These type curves are based on equations developed by Hantush and Jacob and, for convenience, will be referred to as the Hantush-Jacob curves. The four coordinates of the match point are substituted into the following equations to determine T and S :

$$T = \frac{QW(u, r/B)}{4\pi s} \quad (3)$$

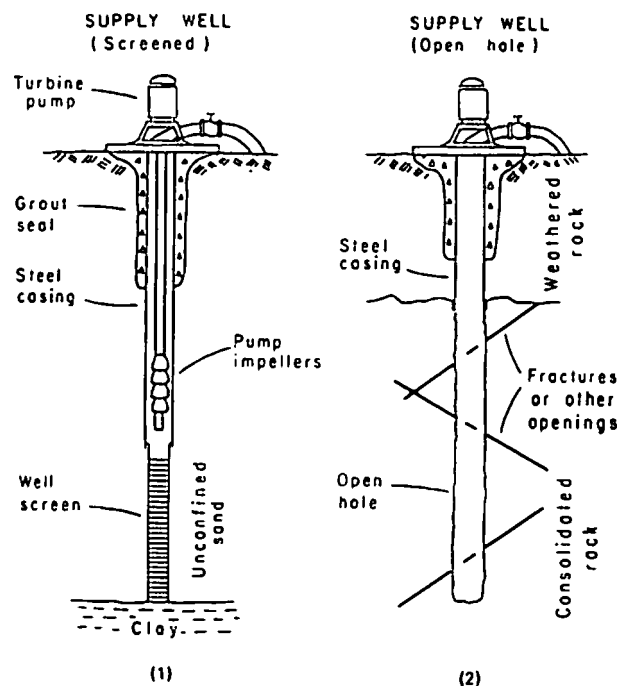
$$S = \frac{4Ttu}{r^2} \quad (4)$$

HANTUSH-JACOB TYPE CURVES FOR AQUIFERS RECEIVING LEAKAGE ACROSS CONFINING BEDS



In planning and conducting aquifer tests, hydrologists must give careful consideration to the hydraulic characteristics of the aquifer and to the type of boundary conditions (either recharge or impermeable) that are likely to exist in the vicinity of the test site. Following completion of the test, the next problem is to select the method of analysis that most closely represents the geologic and hydrologic conditions in the area affected by the test. When these conditions are not well known, the common practice is to prepare a data plot of s versus t on logarithmic paper and match it with the Theis type curve. If the data closely match the type curve, the values of T and S determined by using the Theis equation should be reliable. Significant departures of the data from the type curve generally reflect the presence of lateral boundaries or leaky confining beds. Both the geology of the area and the shape of the data plot may provide clues as to which of these conditions most likely exist. It is important to note, however, that some data plots for tests affected by impermeable boundaries are similar in shape to the Hantush curves.

WELL-CONSTRUCTION METHODS



The seven different methods of well construction in fairly common use are listed in the table. The first four methods are limited to relatively shallow depths and are most commonly employed in the construction of domestic wells. One of the last three methods is usually employed in the construction of municipal and industrial wells and domestic wells in consolidated rock.

The objectives of well construction are to excavate a hole, usually of small diameter in comparison with the depth, to an aquifer and to provide a means for water to enter the hole while rock material is excluded. The means of excavating the hole is different for different methods.

SUITABILITY OF DIFFERENT WELL-CONSTRUCTION METHODS TO GEOLOGIC CONDITIONS

[Modified from U.S. Environmental Protection Agency (1974), table 3]

Characteristics	Dug	Bored	Driven	Jetted	Drilled Percussion (cable tool)	Rotary	
						Hydraulic	Air
Maximum practical depth, in m (ft) -----	15 (50)	30 (100)	15 (50)	30 (100)	300 (1,000)	300 (1,000)	250 (800)
Range in diameter, in cm (in.) -----	1-6 m (3-20 ft)	5-75 (2-30)	3-6 (1-2)	5-30 (2-12)	10-46 (4-18)	10-61 (4-24)	10-25 (4-10)
Unconsolidated material:							
Silt -----	X	X	X	X	X	X	
Sand -----	X	X	X	X	X	X	
Gravel -----	X	X			X	X	
Glacial till -----	X	X			X	X	
Shell and limestone -----	X	X		X	X	X	
Consolidated material:							
Cemented gravel -----	X				X	X	X
Sandstone -----					X	X	X
Limestone -----					X	X	X
Shale -----					X	X	X
Igneous and metamorphic rocks -----					X	X	X

Dug wells constructed with a pickax and shovel were relatively common in rural areas of the eastern and central parts of the country before the 1940's. Such wells are reasonably effective in fine-grained materials, such as glacial till, and thinly bedded sand and clay. The large irrigation ponds that extend below the water table, now being dug by bulldozer or dragline in the Atlantic Coastal Plain, are the modern version of the dug well.

Bored wells are constructed with earth augers turned either by hand or by power equipment and are the modern equivalent of the "hand-dug" well. Bored wells are relatively effective in material of low hydraulic conductivity and in areas underlain by thin surficial layers of silty and clayey sand.

Driven wells are constructed by driving a casing equipped with a screened drive point. Because of their relatively small diameter, these wells are suitable only for relatively permeable surficial aquifers. They are widely used as sources of domestic and farm-water supplies in those parts of the Atlantic and Gulf Coastal Plains underlain by permeable sand.

Jetted wells are constructed by excavating a hole with a high-pressure jet of water. In dense clays, shell beds, and partially cemented layers, it may be necessary to attach a chisel bit to the jet pipe and alternately raise and drop the pipe to cut a hole.

The percussion drilling method (commonly referred to as the cable-tool method) consists of alternately raising and dropping a heavy weight equipped with a chisel bit. The rock at the bottom of the hole is thus shattered and, together with water, forms a slurry that is removed with a bailer. In unconsolidated material, the casing is driven a few feet at a time ahead of the drilling. After drilling to the maximum depth to be reached by the well, a screen is "telescoped" inside the casing and held in place while the casing is pulled back to expose the screen (1). The top of the screen is sealed against the casing by expanding a lead packer. In wells in consolidated

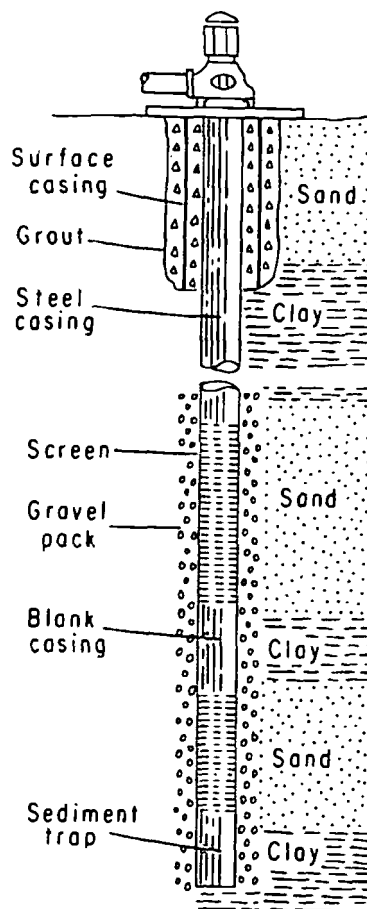
rock, the normal practice is to "seat" the casing firmly in the top of the rock and drill an open hole to the depth required to obtain the needed yield (2).

The *hydraulic rotary method* excavates a hole by rotating a drill pipe to which one of several types of drag or roller bits is attached. Water containing clay is circulated down the drill pipe in the "normal rotary" method and up the annular space, both to cool the bit and to remove the rock cuttings. In the "reverse rotary" method, the drilling fluid is circulated down the annular space and up the drill pipe. Clay in the drilling fluid adheres to the side of the hole and, together with the pressure exerted in the hole by the drilling fluid, prevents caving of the formation material. Thus, in the hydraulic rotary method, it is not necessary to install permanent-well casing during the drilling process. When the hole reaches the desired depth, a line of casing containing sections of screen at the desired intervals is lowered into the well. Hydraulic rotary is the method most commonly employed in drilling large-yield wells in areas underlain by thick sequences of unconsolidated deposits, such as the Atlantic and Gulf Coastal Plains. Where aquifers consist of alternating thin beds of sand and clay, the common practice is to install a gravel envelope around the screens. Such wells are referred to as *gravel packed* (3).

The *air rotary method* is similar to the hydraulic rotary method, except that the drilling fluid is air rather than mud. The air rotary method is suitable only for drilling in consolidated rocks. Most air rotary rigs are also equipped with mud pumps, which permit them to be used in the hydraulic rotary mode for drilling through saturated unconsolidated rock. This method is widely used in the construction of wells in fractured bedrock.

When the construction phase has been completed, it is necessary to begin the phase referred to as *well development*. The objective of this phase is to remove clay, silt, and fine-grained sand from the area adjacent to the screen or open hole so that the well will produce sediment-free water. The simplest method of development is to pump water from the well at a gradually increasing rate, the final rate being larger than the planned production rate. However, this method is not normally successful in screened and gravel-packed wells drilled by the hydraulic rotary method. For these wells, it is necessary to use a surge block or some other means to alternately force water into the formation and pull it back into the well. One of the most effective methods is to pump water under high pres-

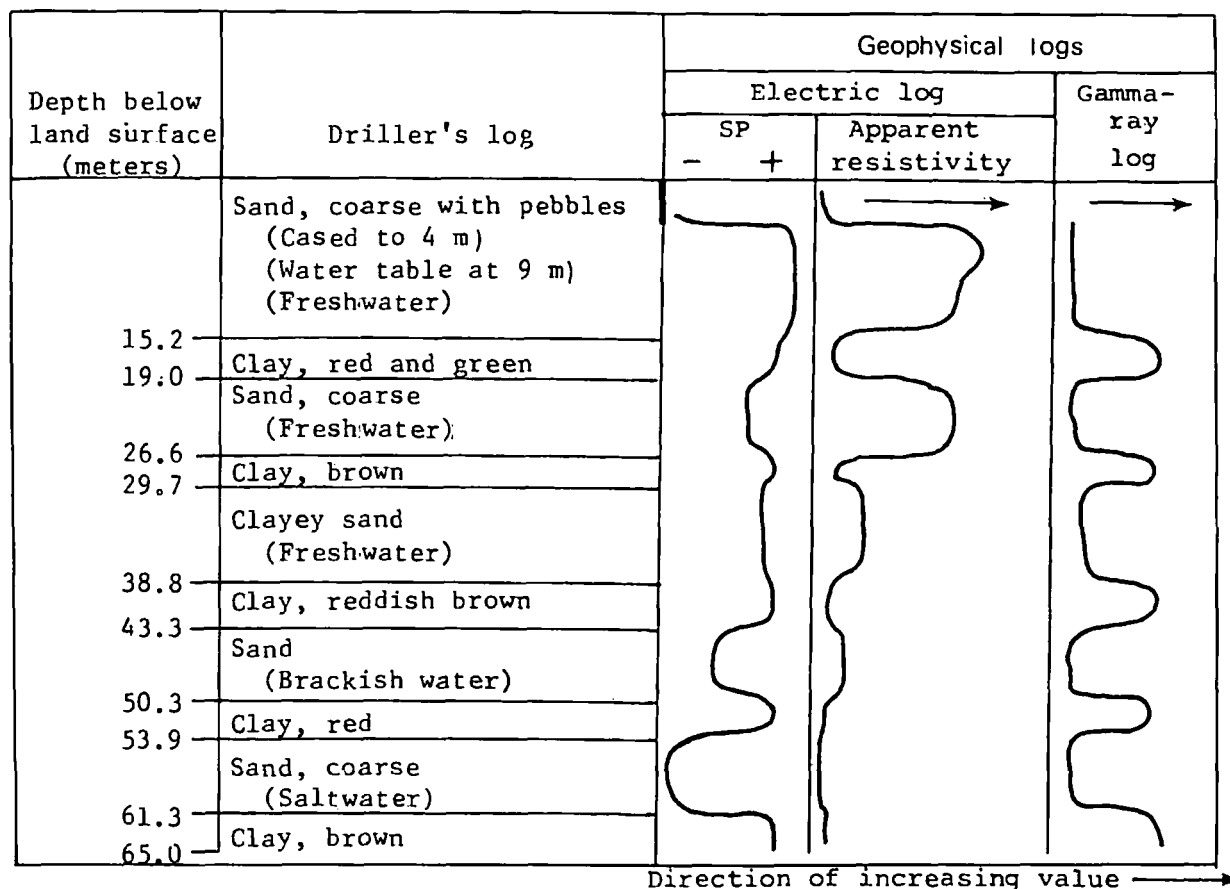
SUPPLY WELL
(Multiple screen, gravel pack)



(3)

sure through orifices directed at the inside of the screen. The coarser grained particles pulled into the well during development tend to settle to the bottom of the well and must be removed with a bailer or pump. Chemicals that disperse clays and other fine-grained particles are also used as an aid in well development.

WELL LOGS



An important part of well construction is determining the character and the thickness of the different layers of material penetrated by the well and the quality of the water in the permeable zones. This information is essential for the installation of casing and for the proper placement of screens. Information on materials penetrated is recorded in the form of "logs." The logs most commonly prepared for supply wells are drillers' logs and geophysical (electric) logs. Copies of logs should be carefully preserved by the well owner as a part of the file on each well.

Drillers' logs consist of written descriptions of the material penetrated by wells. These descriptions are based both on samples of rock cuttings brought to the surface during drilling operations and on changes in the rate of penetration of the drill and in the vibration of the rig. The well driller may also collect samples of the rock cuttings for study by geologists on his staff or those on the staff of State geological surveys or Federal and State water-resources agencies. Descriptions of these samples made by utilizing a microscope and other aids are commonly referred to as a *geologic log* to differentiate them from the driller's log. If the well is to be finished with a screen, the well driller will retain samples of material from the principal water-bearing zones for use in selecting the slot size of screens.

Geophysical logs provide indirect information on the character of rock layers. The most common type of geophysical log, the type normally referred to as an *electric log*, consists of a record of the spontaneous electrical potentials generated in the borehole and the apparent electrical resistivity of the rock units. Several types of electric loggers are available, but nearly all provide continuous graphs of spontaneous potential and resistivity as a sensing device is lowered into and removed from the borehole. Electric logs can be made only in the uncased portion of drill holes. The part of the hole to be logged must also contain drilling mud or water.

The *spontaneous potential log* (which is usually referred to as the *SP log*) is a record of the differences in the voltages of an electrode at the land surface and an electrode in the borehole. Variations in voltage occur as a result of electrochemical and other spontaneous electrical effects. The SP graph is relatively featureless in shallow water wells that penetrate only the freshwater zone. The right-hand boundary of an SP log generally indicates impermeable beds such as clay, shale, and bedrock. The left-hand boundary generally indicates sand, cavernous limestone, and other permeable layers.

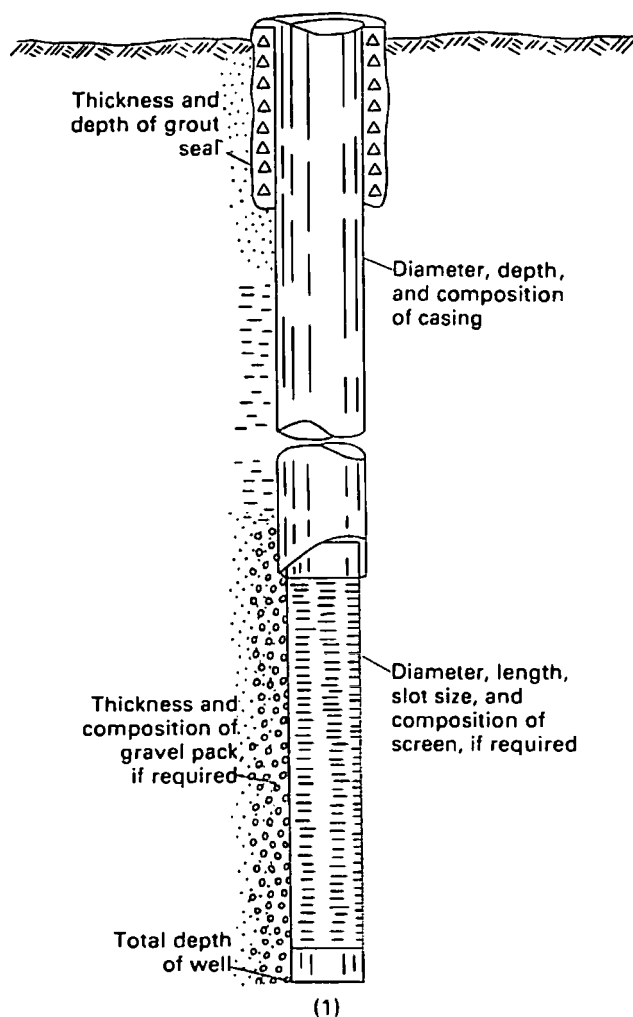
The *resistivity log* is a record of the resistance to the flow of an alternating electric current offered by the rock layers and their contained fluids and the fluid in the borehole. Several different electrode arrangements are used to measure the resistivity of different volumes of material, but the arrangement most commonly used by the water-well industry is referred to as the single-point electrode. The resistivity of water-bearing material depends primarily on the salt content of the water and the porosity of the material. Clay layers normally have a low resistivity because of their large porosity, and the water that they contain tends to be relatively highly mineralized. In contrast, sand layers saturated with freshwater tend to have a high resistivity. Sand layers containing salty water, on the other hand, tend to have a low resistivity resembling that of clay layers. Such layers tend to have a strongly negative spontaneous potential that, viewed together with the resistivity, aids in identification of the layers.

Several other types of geophysical logs are available, including gamma-ray logs that record the rate of emission of gamma rays by different rock layers. In fact, geophysical logging is a complex topic that has been developed, largely by the oil industry, into an advanced technical field. It is being utilized to an increasing extent by the water-well industry, especially in conjunction with the construction of large-yield wells by the hydraulic rotary method.

It is also important, either during well construction or following geophysical logging, to collect, for chemical analyses, water samples from the permeable zones that may supply water to the completed well. The chemical analyses made on these samples should include the concentration of any constituents that are known to be a problem in other supply wells drawing from the aquifer. These constituents might include iron, manganese, chloride, sulfate, nitrate, total dissolved solids, and others. (See "Quality of Ground Water.")

WATER-WELL DESIGN

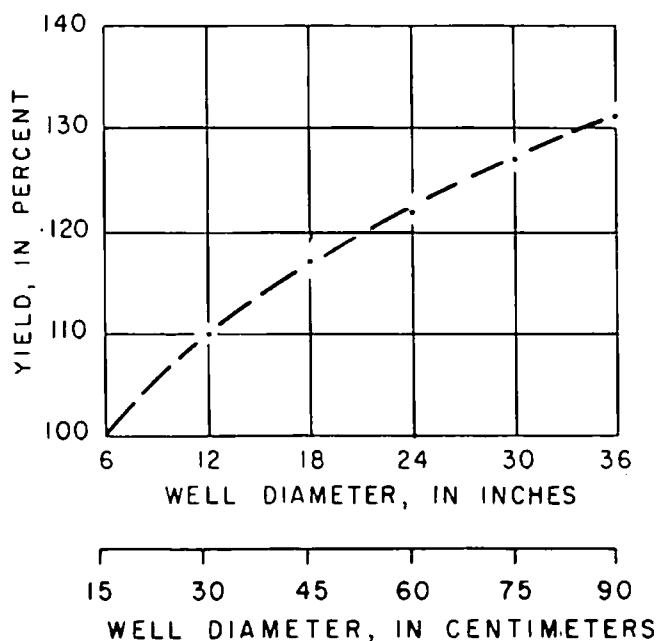
WATER-WELL DESIGNS INCLUDE SPECIFICATIONS ON



Water-well design is the first step in the construction of large-yield wells, such as those required by municipalities and industries. Before the initial design is started, it is necessary to know the yield expected from the well, the depth to aquifers underlying the area, the composition and hydraulic characteristics of those aquifers, and the quality of water in the aquifers. If information on an aquifer is not already available from other wells in the area, it will be necessary to construct a test well before completing the design. The completed design should specify the diameter, the total depth of the well and the position of the screen or open-hole sections, the method of construction, the materials to be used in the construction, and, if a gravel pack is required, its thickness and composition (1).

The well diameter is determined primarily by two factors—the desired yield and the depth to the source aquifer. The diameter has a relatively insignificant effect on the yield (2). For example, doubling the diameter from 15 to 30 centimeters results in only about a 10 percent increase in yield.

WELL DIAMETER VERSUS YIELD AT A CONSTANT DRAWDOWN



(2)

The primary effect of well diameter on yield is related to the size of the pump that can be installed, which, in turn, determines the pumping rate. Data on pumping rate, pump size, and well diameter are given in table 1. In some designs, the upper part of the well is made larger than the remainder of the well in order to accommodate the pump.

Table 1. Data on yield, pump size, and well diameter
(ID, inside diameter; OD, outside diameter)

Anticipated well yield			Nominal size of pump bowls (in.)	Optimum well diameter (in.)
In gal min ⁻¹	In ft ³ min ⁻¹	In m ³ min ⁻¹		
Less than 100	Less than 13	Less than 0.38	4	6 ID
75-175	10-23	.28-.66	5	8 ID
150-400	20-53	.57-1.52	6	10 ID
350-650	47-87	1.33-2.46	8	12 ID
600-900	80-120	2.27-3.41	10	14 OD
850-1,300	113-173	3.22-4.93	12	16 OD
1,200-1,800	160-240	4.55-6.82	14	20 OD
1,600-3,000	213-400	6.06-11.37	16	24 OD

The screen diameter and length, the slot size, and the pumping rate determine the velocity at which water passes through the screen (that is, the so-called "entrance velocity"). The entrance velocity should not normally exceed about 6 ft min⁻¹ (1.8 m min⁻¹). If the anticipated yield in cubic feet per minute shown in table 1 is divided by 6 ft min⁻¹, the result is the minimum open area of screen needed in square feet.¹ Because screen openings are partially blocked by aquifer or gravel-packed material, some well drillers increase the open area needed by 50 to 100 percent to assure that entrance velocities will not be excessive.

The amount of open area per unit length of well screen depends on the diameter, the slot size, and the type of screen. Table 2 shows, for example, the open area of screens manufactured by the Edward E. Johnson Co.² If the open area needed in square feet is divided by the open area per linear foot, the result is the length of screen, in feet, required to provide the yield without exceeding the recommended entrance velocity.

¹Because dimensions of screens manufactured in the United States are still expressed in inches or feet, these units will be used in this discussion. SI units will be added only where it is useful to do so.

²The use of a company name is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

The depth to the source aquifer also affects the well diameter to the extent that wells expected to reach aquifers more than a few hundred feet below land surface must be large enough to accept the larger diameter cable tool or drill rods required to reach these depths.

The total depth of a well depends on the depth below land surface to the lowest water-bearing zone to be tapped.

Table 2. Open areas of Johnson well screens

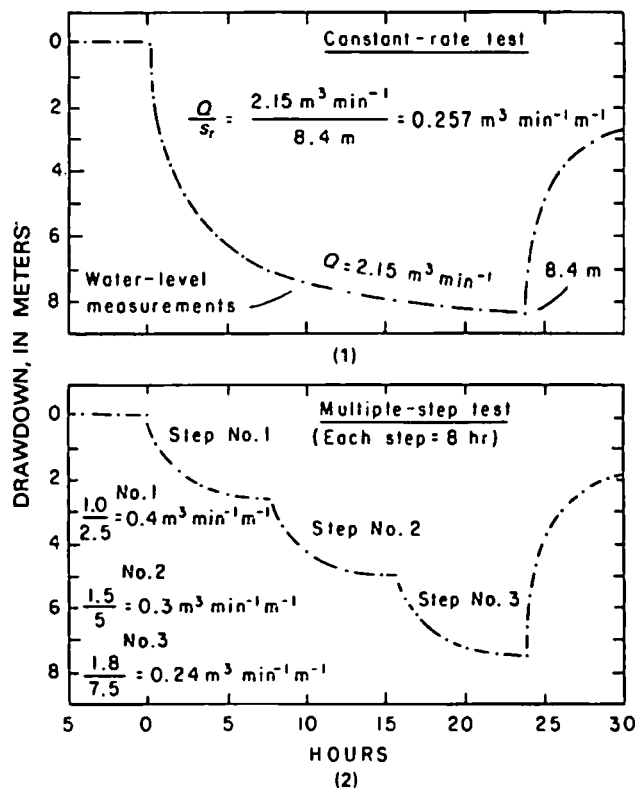
(n denotes width of screen opening in thousandths (1/1,000) of an inch. For example, slot no. 10 indicates an opening 10/1,000 or 0.01 inch)

Nominal screen diameter (in.)	Open areas per linear foot of screen for slot no. n (ft ²)						
	10	20	40	60	80	100	150
4 -----	0.17	0.30	0.47	0.60	0.68	0.64	0.76
6 -----	.17	.32	.53	.69	.81	.92	.97
8 -----	.22	.41	.69	.90	1.05	1.19	1.28
10 -----	.28	.51	.87	.96	1.15	1.30	1.60
12 -----	.26	.50	.87	1.13	1.37	1.55	1.89
14 -----	.30	.56	.96	1.26	1.53	1.74	2.11
16 -----	.34	.64	1.11	1.45	1.75	1.98	2.42

The position of the screen depends on the thickness and composition of the source aquifer and whether the well is being designed to obtain the maximum possible yield. Because withdrawals from unconfined aquifers result in dewatering of the aquifers, wells in these aquifers are normally screened only in the lower part in order to obtain the maximum available drawdown. In confined aquifers, screens are set either in the most permeable part of the aquifer or, where vertical differences in hydraulic conductivity are not significant, in the middle part of the aquifer.

The length of the screen specified in the well design depends on the thickness of the aquifer, the desired yield, whether the aquifer is unconfined or confined, and economic considerations. When an attempt is being made to obtain the maximum available yield, screens are normally installed in the lower 30 to 40 percent of unconfined aquifers and in the middle 70 to 80 percent of confined aquifers.

WELL-ACCEPTANCE TESTS AND WELL EFFICIENCY



Many supply-well contracts require a "guaranteed" yield, and some stipulate that the well reach a certain level of "efficiency." Most contracts also specify the length of the "draw-down test" that must be conducted to demonstrate that the yield requirement is met. For example, many States require that tests of public-supply wells be at least 24 hours. Tests of most industrial and irrigation wells probably do not exceed about 8 hours.

Well-acceptance tests, if properly conducted, not only can confirm the yield of a well and the size of the production pump that is needed but can also provide information of great value in well operation and maintenance. Such tests should, therefore, be conducted with the same care as aquifer tests made to determine the hydraulic characteristics of aquifers. A properly conducted test will include:

1. Determination of well interference from nearby pumping wells, based on accurate water-level measurements made before the drawdown test.
2. A pumping rate that is either held constant during the entire test (1) or increased in steps of equal length (2). The pumping rate during each step should be held constant, and the length of each step should be at least 2 hours.

Of these requirements, the constant, carefully regulated pumping rate or rates and the accurate water-level measurements are the most important. When a constant-rate well-acceptance test has been completed, the drawdown data can be analyzed to determine the aquifer transmissivity. (See "Single-Well Tests.")

Many well-acceptance tests are made with temporary pump installations, usually powered with a gasoline or diesel engine. Instead of maintaining a constant rate for the duration of the test, the engine is frequently stopped to add fuel or to check the oil level or for numerous other reasons. The rate may also be increased and decreased on an irregular, unplanned schedule or, more commonly, gradually reduced during the test in an effort to maintain a pumping level above the pump intake. In such tests, the "yield" of the well is normally reported to be the final pumping rate.

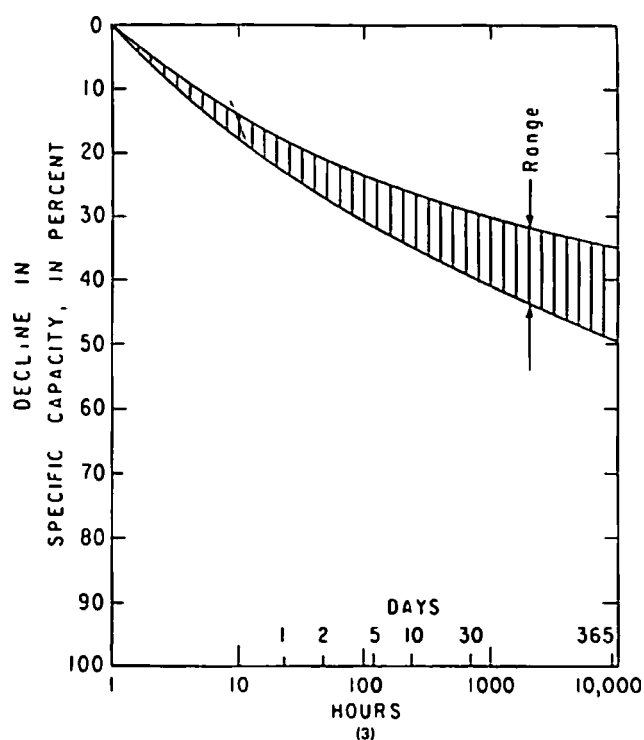
Determining the long-term yield of a well from data collected during a short-period well-acceptance test is one of the most important, practical problems in ground-water hydrology. Two of the most important factors that must be considered are the extent to which the yield will decrease if the well is pumped continuously for periods longer than the test period and the effect on the yield of changes in the static (regional) water level from that existing at the time of the test.

When data are available only from the production well and when the pumping rate was not held constant during the acceptance test, the estimate of the long-term yield must usually be based on an analysis of specific-capacity data. Specific capacity is the yield per unit of drawdown and is determined by dividing the pumping rate at any time during the test by the drawdown at the same time. Thus,

$$\text{specific capacity} = \frac{\text{pumping rate}}{\text{drawdown}} = \frac{Q}{s_t} \quad (1)$$

Before the development of steady-state conditions, a part of the water pumped from an aquifer is derived from storage. The time required for steady-state conditions to develop depends largely on the distance to and characteristics of the recharge and discharge areas and the hydraulic characteristics of the aquifer. The time required to reach a steady state is independent of the pumping rate. At some places in some aquifers, a steady-state condition will be reached in several days, whereas, in others, six months to a year may be required; in some arid areas, a steady-state condition may never be achieved. Depending on the length of the well-acceptance test and the period required to reach a steady-state condition, it may be appropriate, in estimating the long-term yield of a well, to use a specific capacity smaller than that determined during the test.

DECLINE IN SPECIFIC CAPACITY WITH TIME
AT A CONTINUOUS PUMPING RATE



Sketch 3 shows the decline in specific capacity with time when a well is pumped continuously at a constant rate and all the water is derived from storage in an isotropic and homogeneous aquifer. For convenience in preparing the sketch, a value of 100 percent was assigned to the specific capacity 1 hour after the pump was started. The rate at which the specific capacity decreases depends on the decline of the water level due to depletion of storage and on the hydraulic characteristics of the aquifer. Differences in the rate for different aquifers are indicated by the width of the band on the sketch. When withdrawals are derived entirely from storage, the specific capacity will decrease about 40 percent during the first year.

In predicting the long-term yield of a well, it is also necessary to consider changes in the static water level resulting from seasonal and long-term variations in recharge and declines due to other withdrawals from the aquifer. The long-term yield is equal to the specific capacity, determined from the well-acceptance test, and reduced as necessary to compensate for the long-term decline discussed in the above paragraph, multiplied by the available drawdown.

The available drawdown at the time of a well-acceptance test is equal to the difference between the static water level at that time and the lowest pumping level that can be imposed on the well. The lowest pumping level in a screened well is normally considered to be a meter or two above the top of the screen. In an unscreened (open-hole) well, it may be at the

level of either the highest or the lowest water-bearing opening penetrated by the well. The choice of the highest or the lowest opening depends on the chemical composition of the water and whether water cascading from openings above the pumping level results in precipitation of minerals on the side of the well and on the pump intake. If such precipitation is expected, the maximum pumping level should not be below the highest opening. The yield of a well is not increased by a pumping level below the lowest opening, and the maximum yield may, in fact, be attained at a much higher level.

To predict the maximum continuous long-term yield, it is necessary to estimate how much the static water level, and thus the available drawdown, may decline from the position that it occupied during the acceptance test. Records of water-level fluctuations in long-term observation wells in the area will be useful in this effort.

Well efficiency is an important consideration both in well design and in well construction and development. The objective, of course, is to avoid excessive energy costs by designing and constructing wells that will yield the required water with the least drawdown.

Well efficiency can be defined as the ratio of the drawdown (s_a) in the aquifer at the radius of the pumping well to the drawdown (s_l) inside the well. (See "Single-Well Tests.") Thus, the equation

$$E = \frac{s_a}{s_l} \times 100 \quad (2)$$

expresses well efficiency as a percentage.

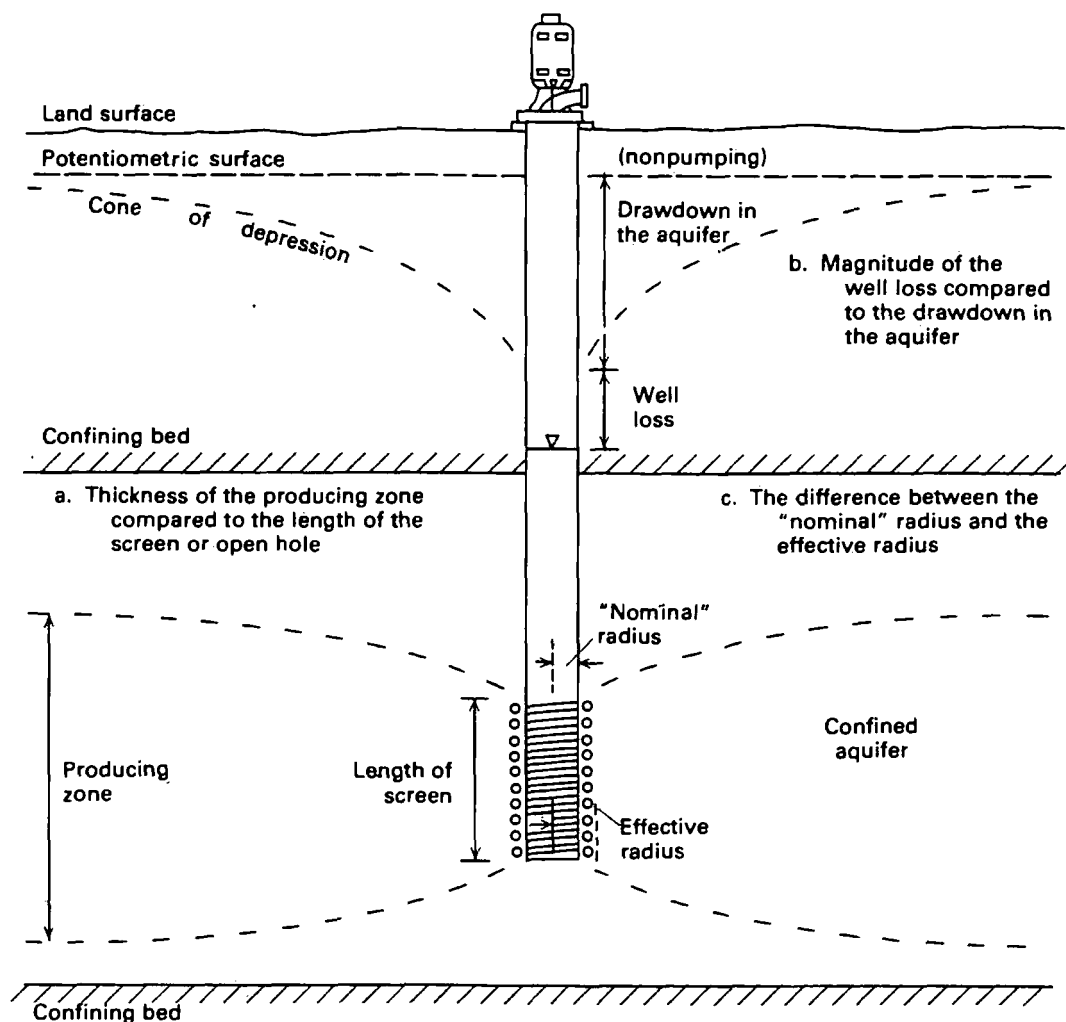
Drawdowns in pumping wells are measured during well-acceptance tests. Determining the drawdown in the aquifer is a much more difficult problem. It can be calculated if the hydraulic characteristics of the aquifer, including the effect of boundary conditions, are known.

The difference between s_l and s_a is attributed to head losses as water moves from an aquifer into a well and up the well bore. These well losses can be reduced by reducing the entrance velocity of the water, which can be done by installing the maximum amount of screen and pumping at the lowest acceptable rate. Tests have been devised to determine well losses, and the results can be used to determine well efficiency. However, these tests are difficult to conduct and are not widely used. Because of difficulties in determining s_a , well efficiency is generally specified in terms of an "optimum" specific capacity based on other producing wells in the vicinity.

Under the best conditions, an efficiency of about 80 percent is the maximum that is normally achievable in most screened wells. Under less than ideal conditions, an efficiency of 60 percent is probably more realistic.

SPECIFIC CAPACITY AND TRANSMISSIVITY

FACTORS AFFECTING ESTIMATES OF TRANSMISSIVITY BASED ON SPECIFIC CAPACITY



FACTORS AFFECTING ESTIMATES OF TRANSMISSIVITY BASED ON SPECIFIC CAPACITY

The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the construction and other features of the well. Values of specific capacity, available for many supply wells for which aquifer-test data are not available, are widely used by hydrologists to estimate transmissivity. Such estimates are used to evaluate regional differences in transmissivity and to prepare transmissivity maps for use in models of ground-water systems.

The factors that affect specific capacity include:

1. The transmissivity of the zone supplying water to the well, which, depending on the length of the screen or open hole, may be considerably less than the transmissivity of the aquifer.
2. The storage coefficient of the aquifer.
3. The length of the pumping period.
4. The effective radius of the well, which may be significantly greater than the "nominal" radius.
5. The pumping rate.

The Theis equation can be used to evaluate the effect of the first four factors on specific capacity. The last factor, pumping rate, affects the well loss and can be determined only from a stepped-rate test or an aquifer test in which drawdowns are measured in both the pumping well and observation wells.

The Theis equation, modified for the determination of transmissivity from specific capacity, is

$$T = \frac{W(u)}{4\pi} \times \frac{Q}{s} \quad (1)$$

where T is transmissivity, Q/s is specific capacity, Q is the pumping rate, s is the drawdown, and $W(u)$ is the well function of u , where

$$u = \frac{r^2 S}{4Tt} \quad (2)$$

where r is the effective radius of the well, S is the storage coefficient, and t is the length of the pumping period preceding the determination of specific capacity.

For convenience in using equation 1, it is desirable to express $W(u)/4\pi$ as a constant. To do so, it is first necessary to determine values for u and, using a table of values of u (or $1/u$) and $W(u)$, determine the corresponding values for $W(u)$.

Values of u are determined by substituting in equation 2 values of T , S , r , and t that are representative of conditions in the area. To illustrate, assume, in an area under investigation and for which a large number of values of specific capacity are available, that:

1. The principal aquifer is confined, and aquifer tests indicate that it has a storage coefficient of about 2×10^{-4} and a transmissivity of about $11,000 \text{ ft}^2 \text{ d}^{-1}$.
2. Most supply wells are 8 in. (20 cm) in diameter (radius, 0.33 ft).
3. Most values of specific capacity are based on 12-hour well-acceptance tests ($t = 0.5 \text{ d}$).

Substituting these values in equation 2, we obtain

$$u = \frac{r^2 S}{4Tt} = \frac{(0.33 \text{ ft})^2 \times (2 \times 10^{-4})}{4 \times (11,000 \text{ ft}^2 \text{ d}^{-1}) \times 0.5 \text{ d}}$$

$$u = \frac{2.22 \times 10^{-5} \text{ ft}^2}{2.2 \times 10^4 \text{ ft}^2} = 1.01 \times 10^{-9}$$

A table of values of $W(u)$ for values of $1/u$ is contained in the section of this report entitled "Aquifer Tests." Therefore, the value of u determined above must be converted to $1/u$, which is 9.91×10^8 , and this value is used to determine the value of $W(u)$. Values of $W(u)$ are given for values of $1/u$ of 7.69×10^8 and 10×10^8 but not for 9.91×10^8 . However, the value of 10 is close enough to 9.91 for the purpose of estimating transmissivity from specific capacity. From the table, we determine that, for a value of $1/u$ of 10×10^8 , the value of $W(u)$ is 20.15. Substituting this value in equation 1, we find the constant $W(u)/4\pi$ to be 1.60.

Equation 1 is in consistent units. However, transmissivity is commonly expressed in the United States in units of square feet per day, pumping rates are reported in units of gallons per minute, and drawdowns are measured in feet. To obtain an equation that is convenient to use, it is desirable to convert equation 1 to these inconsistent units. Thus

$$T = 1.60 \times \frac{1,440 \text{ min}}{\text{d}} \times \frac{\text{ft}^2}{7.48 \text{ gal}} \times \frac{Q}{s}$$

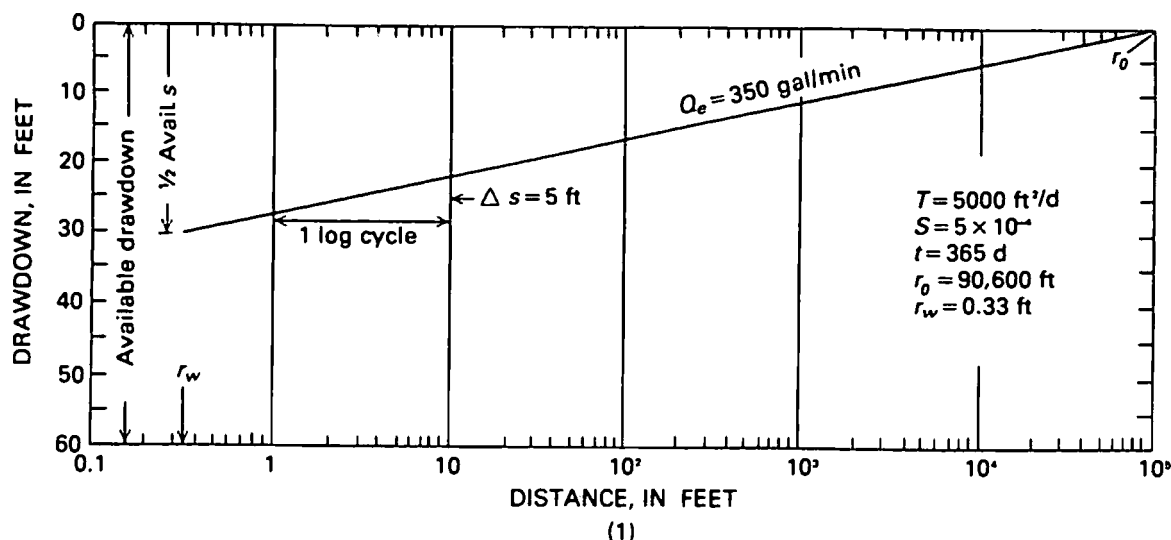
$$T = 308 \frac{Q}{s} \text{ or } 300 \frac{Q}{s} \text{ (rounded)} \quad (3)$$

Many readers will find it useful at this point to substitute different values of T , S , r , and t in equation 2 to determine how different values affect the constant in equation 3. In using equation 3, modified as necessary to fit the conditions in an area, it is important to recognize its limitations. Among the most important factors that affect its use are the accuracy with which the thickness of the zone supplying water to the well can be estimated, the magnitude of the well loss in comparison with drawdown in the aquifer, and the difference between the "nominal" radius of the well and its effective radius.

Relative to these factors, the common practice is to assume that the value of transmissivity estimated from specific capacity applies only to the screened zone or to the open hole. To apply this value to the entire aquifer, the transmissivity is divided by the length of the screen or open hole (to determine the hydraulic conductivity per unit of length), and the result is multiplied by the entire thickness of the aquifer. The value of transmissivity determined by this method is too large if the zone supplying water to the well is thicker than the length of the screen or the open hole. Similarly, if the effective radius of the well is larger than the "nominal" radius (assuming that the "nominal" radius is used in equation 2), the transmissivity based on specific capacity again will be too large.

On the other hand, if a significant part of the drawdown in the pumping well is due to well loss, the transmissivity based on specific capacity will be too small. Whether the effect of all three of these factors cancels depends on the characteristics of both the aquifer and the well. Where a sufficient number of aquifer tests have been conducted, it may be feasible to utilize the results to modify the constant in equation 3 to account for the effect of these factors.

WELL-FIELD DESIGN



The development of moderate to large supplies of water from most aquifers requires more than one well; in other words, it requires what is commonly referred to as a well field. Consequently, the design of well fields is an important problem in ground-water development. The objective of well-field design is to obtain the required amount of water for the least cost, including the initial construction cost of wells and pipelines, the cost of operation and maintenance, and the cost of well replacement.

The final product of a design is a plan showing the arrangement and spacing of wells and specifications containing details on well construction and completion, including information on well diameter, depth, and position of screens or open hole, the type of casing and screens, and the type, size, and setting of pumps.

The key elements in well-field design are the total quantity of water to be obtained from the field, the rate at which each well can be pumped (which determines the number of wells that will be required), and the spacing of the wells.

The pumping rate for each well can be estimated with Jacob's modification of the Theis equation. (See "Distance-Drawdown Analysis.") It depends on the transmissivity and storage coefficient of the aquifer, the distance to and nature of lateral boundaries, the hydraulic characteristics of confining beds, the available drawdown, and the pumping period. For the purpose of this discussion, we will not consider the effect of boundaries or confining beds. (For a discussion of available drawdown, see "Well Interference" and "Well-Acceptance Tests and Well Efficiency.") The pumping period is normally taken as 1 year. To determine the pumping rate, Jacob's equations are solved as follows:

$$r_o^2 = \frac{2.25Tt}{S} \quad (1)$$

$$Q_e = 2.7T\Delta s \quad (2)$$

where r_o is the distance from the pumping well, in meters (or feet), to the point of zero drawdown on a semilogarithmic graph in which drawdown is on the arithmetic scale and distance is on the logarithmic scale, T is aquifer transmissivity, in square meters per day (or square feet per day), t is 365 days (1 year), S is the aquifer storage coefficient (dimensionless), Δs is the drawdown, in meters (or feet), across one log cycle along a line connecting point r_o and a point at the proposed radius of the pumping well at which the drawdown equals about half the available drawdown,¹ and Q_e is the first estimate of the pumping rate in cubic meters per day (or cubic feet per day). To convert to gallons per minute, when Q_e is in cubic meters per day, divide by 5.45 (when Q_e is in cubic feet per day, divide by 192).

The estimated pumping rate Q_e is divided into the total quantity of water needed from the well field in order to determine the number of wells that will be needed. The next step is to determine the optimum well spacing. This determination involves both hydrologic and economic considerations. The hydrologic considerations include the following:

1. The minimum distance between pumping wells should be at least twice the aquifer thickness if the wells are open to less than about half the aquifer thickness.
2. Wells near recharging boundaries should be located along a line parallel to the boundary and as close to the boundary as possible.
3. Wells near impermeable boundaries should be located along a line perpendicular to the boundary and as far from the boundary as possible.

¹At this point, we use half the available drawdown in order to get a first estimate of well loss and well interference. If we determine that, at a pumping rate of Q_e , the drawdown in the aquifer is less than the available drawdown and the drawdown in the well is above the top of the screen, we can assume a larger value of s and recompute Q_e . It is important also to note that, in the initial determination of available drawdown, the seasonal fluctuation of static water level must be considered.

The primary economic considerations involved in well spacing include the cost of wells and pumps, power costs, and the cost of interconnecting pipelines and powerlines. The closer wells are spaced, the smaller the yield of each well because of well interference. The smaller yield of closely spaced wells means that more wells and well pumps are required, and power costs are higher. The cost of the additional wells and the larger pumping costs must be evaluated in relation to the cost of shorter interconnecting pipelines and powerlines.

Sketch 1 shows a distance-drawdown graph for a pumping well at the end of a continuous pumping period of one year for an aquifer having a transmissivity (T) of $5,000 \text{ ft}^2 \text{ d}^{-1}$ ($465 \text{ m}^2 \text{ d}^{-1}$), a storage coefficient (S) of 5×10^{-4} , and an available drawdown of 60 ft (18 m). The assumed radius of the pumping well (r_w) is 0.33 ft (diameter, 8 in. or 20 cm). When one-half the available drawdown is used, along with the other values as stated, equation 2 yields an estimated pumping rate (Q_e) of 350 gal min^{-1} or $504,000 \text{ gal d}^{-1}$.²

To illustrate the use of sketch 1 in analyzing the well-spacing problem, we will assume that a yield of $1,500,000 \text{ gal d}^{-1}$ ($1,040 \text{ gal min}^{-1}$) is desired from the aquifer. This yield can be obtained from three wells producing $500,000 \text{ gal d}^{-1}$ (350 gal min^{-1}) each. Assume that the wells are located on a straight line and are numbered 1, 2, and 3. Well 2, being in the middle, will obviously have the most well interference and,

therefore, the largest drawdown. How close can it be to wells 1 and 3 without its drawdown exceeding the available drawdown of 60 ft?

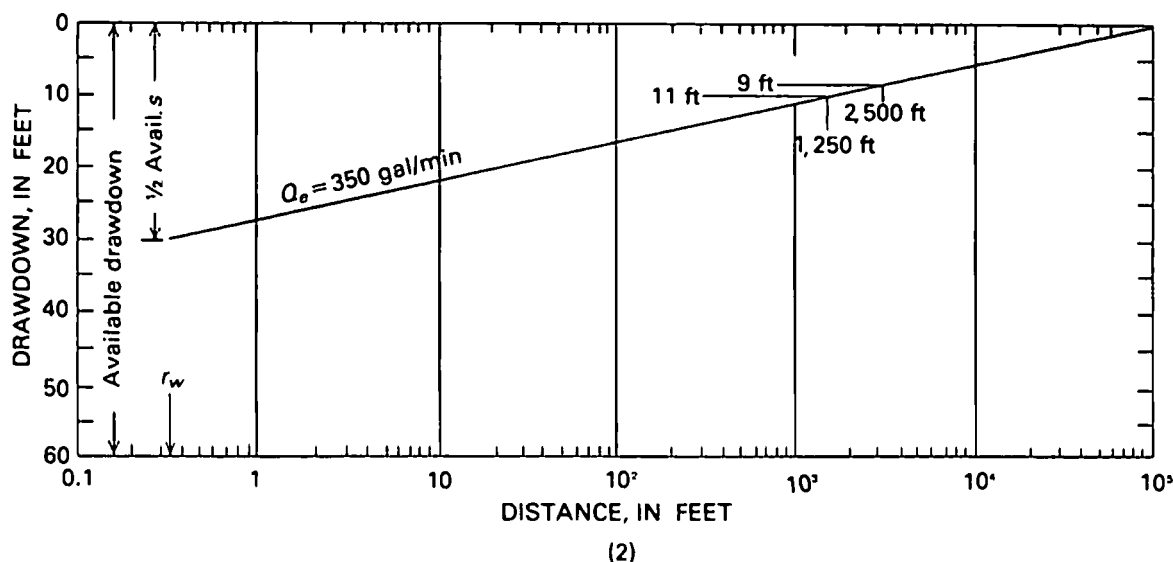
When well 2 is pumped at a rate of 350 gal min^{-1} , the drawdown in the aquifer at the radius of the well will be one-half the available drawdown, or 30 ft. The remaining 30 ft of the available drawdown must be apportioned between well loss in well 2 and interference from wells 1 and 3. According to sketch 1, if well 2 were 100 percent efficient, its specific capacity would be

$$\frac{350 \text{ gal min}^{-1}}{30 \text{ ft}} = 11.7 \text{ gal min}^{-1} \text{ ft}^{-1}$$

We will assume, however, that well 2 will be only 80 percent efficient. If so, its specific capacity will be

$$\frac{11.7 \text{ gal min}^{-1} \text{ ft}^{-1}}{100 \text{ percent}} = \frac{X}{80 \text{ percent}} = 9.4 \text{ gal min}^{-1} \text{ ft}^{-1}$$

and a yield of 350 gal min^{-1} will produce a drawdown in well 2 of about 37 ft ($350/9.4$). Subtracting 37 ft from 60 ft leaves a difference of 23 ft, which can be assigned to well interference from wells 1 and 3. If fractional feet are ignored, the amount of interference by each well is about 11 ft.

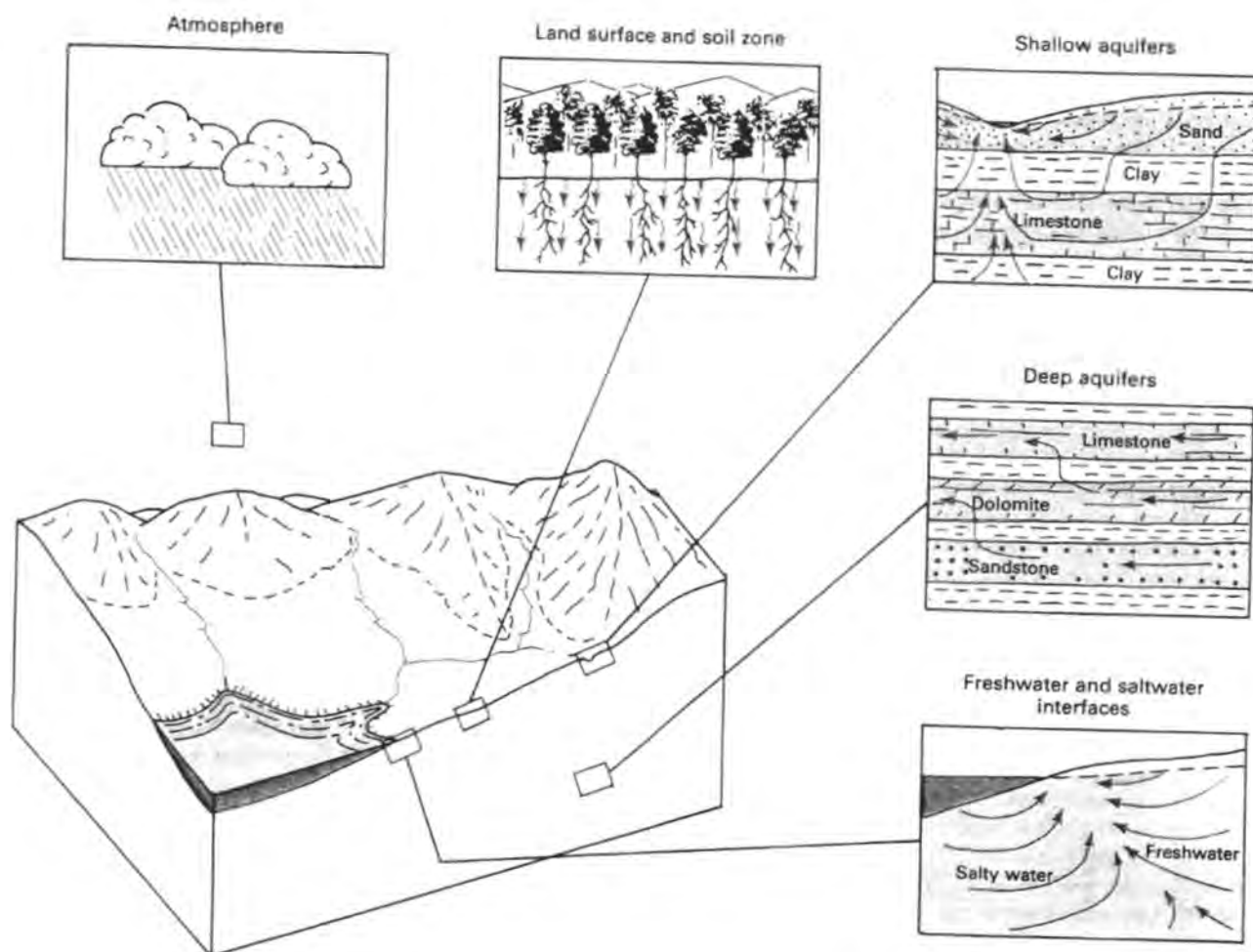


Sketch 2 shows that a well pumping 350 gal min^{-1} from the aquifer will produce a drawdown of 11 ft at a distance of about 1,250 ft. Therefore, the spacing between wells 1 and 2

and between wells 2 and 3 would have to be 1,250 ft in order not to exceed the available drawdown at well 2. With this spacing, wells 1 and 3 would be 2,500 ft apart. Sketch 2 shows the drawdown at 2,500 ft to be about 9 ft. Consequently, the drawdowns in both wells 1 and 3 would be 58 ft, or about 2 ft less than the drawdown in well 2.

²Inch-pound units are used in this example for the convenience of those readers who are not yet accustomed to using metric units.

QUALITY OF GROUND WATER



THE CHEMICAL CHARACTERISTICS OF GROUND WATER ARE DETERMINED BY THE CHEMICAL AND BIOLOGICAL REACTIONS IN THE ZONES THROUGH WHICH THE WATER MOVES

Water consists of two atoms of hydrogen and one of oxygen, which give it a chemical formula of H_2O . Water frequently is referred to as the universal solvent because it has the ability to dissolve at least small amounts of almost all substances that it contacts. Of the domestic water used by man, ground water usually contains the largest amounts of dissolved solids. The composition and concentration of substances dissolved in unpolluted ground water depend on the chemical composition of precipitation, on the biologic and chemical reactions occurring on the land surface and in the soil zone, and on the mineral composition of the aquifers and confining beds through which the water moves.

The concentrations of substances dissolved in water are commonly reported in units of weight per volume. In the International System (SI), the most commonly used units are milligrams per liter. A milligram equals 1/1,000 (0.001) of a gram, and a liter equals 1/1,000 of a cubic meter, so that 1 mg/L equals 1 gram m^{-3} .¹ Concentrations of substances in water were reported for many years in the United States in

units of weight per weight. Because the concentration of most substances dissolved in water is relatively small, the weight per weight unit commonly used was parts per million (ppm). In inch-pound units, 1 ppm is equal to 1 lb of a substance dissolved in 999,999 lb of water, the weight of the solution thus being 1 million pounds.

The quality of ground water depends both on the substances dissolved in the water and on certain properties and characteristics that these substances impart to the water. Table 1 contains information on dissolved inorganic substances that normally occur in the largest concentrations and are most likely to affect water use. Table 2 lists other characteristics of water that are commonly reported in water analyses and that may affect water use. Dissolved constituents for which concentration limits have been established for drinking water are discussed in "Pollution of Ground Water."

¹To put these units in possibly more understandable terms, 1 mg/L equals 1 oz of a substance dissolved in 7,500 gal of water.

Table 1. Natural inorganic constituents commonly dissolved in water that are most likely to affect use of the water

Substance	Major natural sources	Effect on water use	Concentrations of significance (mg/L) ¹
Bicarbonate (HCO ₃) and carbonate (CO ₃) ----	Products of the solution of carbonate rocks, mainly limestone (CaCO ₃) and dolomite (CaMgCO ₃), by water containing carbon dioxide.	Control the capacity of water to neutralize strong acids. Bicarbonates of calcium and magnesium decompose in steam boilers and water heaters to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	150-200
Calcium (Ca) and magnesium (Mg) -----	Soils and rocks containing limestone, dolomite, and gypsum (CaSO ₄). Small amounts from igneous and metamorphic rocks.	Principal cause of hardness and of boiler scale and deposits in hot-water heaters.	25-50
Chloride (Cl) -----	In inland areas, primarily from seawater trapped in sediments at time of deposition; in coastal areas, from seawater in contact with freshwater in productive aquifers.	In large amounts, increases corrosiveness of water and, in combination with sodium, gives water a salty taste.	250
Fluoride (F) -----	Both sedimentary and igneous rocks. Not widespread in occurrence.	In certain concentrations, reduces tooth decay; at higher concentrations, causes mottling of tooth enamel.	0.7-1.2 ²
Iron (Fe) and manganese (Mn) -----	Iron present in most soils and rocks; manganese less widely distributed.	Stain laundry and are objectionable in food processing, dyeing, bleaching, ice manufacturing, brewing, and certain other industrial processes.	Fe > 0.3, Mn > 0.05
Sodium (Na) -----	Same as for chloride. In some sedimentary rocks, a few hundred milligrams per liter may occur in freshwater as a result of exchange of dissolved calcium and magnesium for sodium in the aquifer materials.	See chloride. In large concentrations, may affect persons with cardiac difficulties, hypertension, and certain other medical conditions. Depending on the concentrations of calcium and magnesium also present in the water, sodium may be detrimental to certain irrigated crops.	69 (irrigation), 20-170 (health) ³
Sulfate (SO ₄) -----	Gypsum, pyrite (FeS), and other rocks containing sulfur (S) compounds.	In certain concentrations, gives water a bitter taste and, at higher concentrations, has a laxative effect. In combination with calcium, forms a hard calcium carbonate scale in steam boilers.	300-400 (taste), 600-1,000 (laxative)

¹A range in concentration is intended to indicate the general level at which the effect on water use might become significant.

²Optimum range determined by the U.S. Public Health Service, depending on water intake.

³Lower concentration applies to drinking water for persons on a strict diet; higher concentration is for those on a moderate diet.

Table 2. Characteristics of water that affect water quality

Characteristic	Principal cause	Significance	Remarks
Hardness -----	Calcium and magnesium dissolved in the water.	Calcium and magnesium combine with soap to form an insoluble precipitate (curd) and thus hamper the formation of a lather. Hardness also affects the suitability of water for use in the textile and paper industries and certain others and in steam boilers and water heaters.	USGS classification of hardness (mg/L as CaCO ₃): 0-60: Soft 61-120: Moderately hard 121-180: Hard More than 180: Very hard
pH (or hydrogen-ion activity) -----	Dissociation of water molecules and of acids and bases dissolved in water.	The pH of water is a measure of its reactive characteristics. Low values of pH, particularly below pH 4, indicate a corrosive water that will tend to dissolve metals and other substances that it contacts. High values of pH, particularly above pH 8.5, indicate an alkaline water that, on heating, will tend to form scale. The pH significantly affects the treatment and use of water.	pH values: less than 7, water is acidic; value of 7, water is neutral; more than 7, water is basic.
Specific electrical conductance ---	Substances that form ions when dissolved in water.	Most substances dissolved in water dissociate into ions that can conduct an electrical current. Consequently, specific electrical conductance is a valuable indicator of the amount of material dissolved in water. The larger the conductance, the more mineralized the water.	Conductance values indicate the electrical conductivity, in micromhos, of 1 cm ³ of water at a temperature of 25°C.
Total dissolved solids -----	Mineral substances dissolved in water.	Total dissolved solids is a measure of the total amount of minerals dissolved in water and is, therefore, a very useful parameter in the evaluation of water quality. Water containing less than 500 mg/L is preferred for domestic use and for many industrial processes.	USGS classification of water based on dissolved solids (mg/L): Less than 1,000: Fresh 1,000-3,000: Slightly saline 3,000-10,000: Moderately saline 10,000-35,000: Very saline More than 35,000: Briny

POLLUTION OF GROUND WATER

Pollution of ground water is receiving increased attention from both Federal and State regulatory agencies and from water users. As a result, pollution has been found to be much more widespread than we had believed only a few years ago. This attention has also resulted in widespread recognition of the facts that polluted ground water may pose a serious threat to health that is often not apparent to those affected and that purification of polluted ground-water systems may require centuries or the expenditure of huge sums of money. These facts alone make it imperative that the pollution of ground water by harmful substances absolutely be avoided to the maximum possible extent.

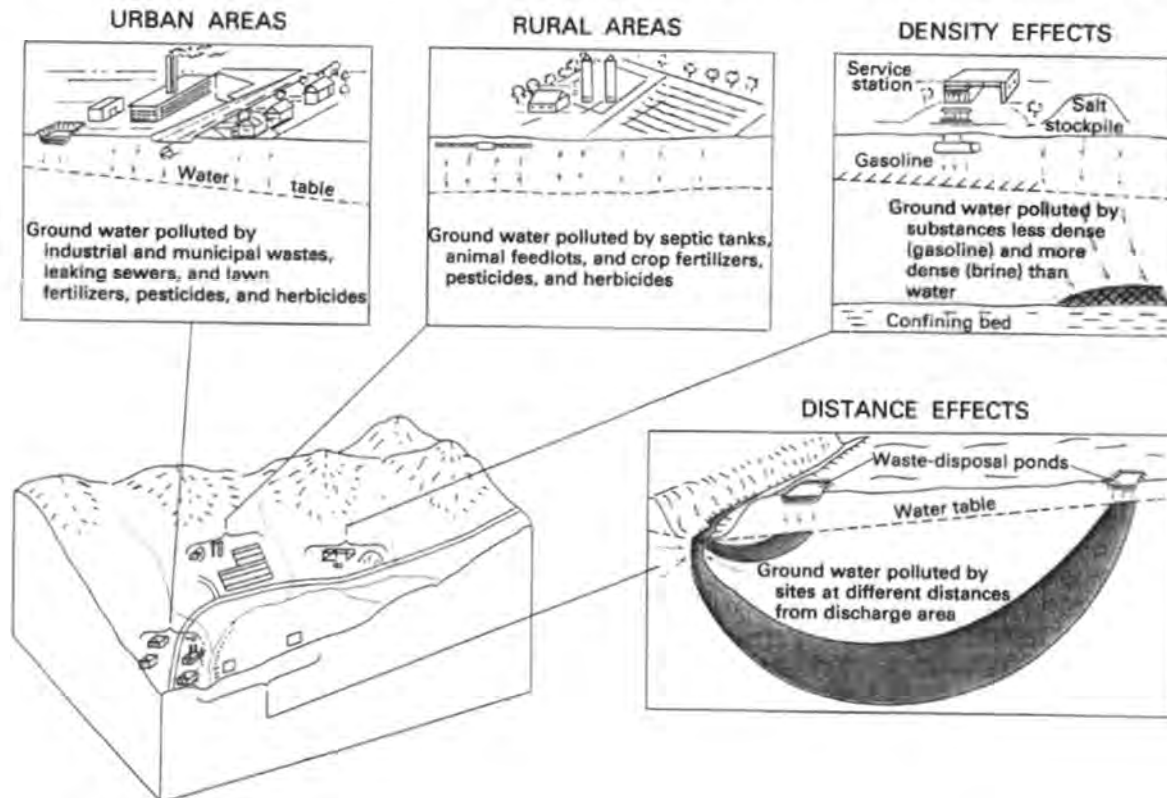
Pollution of ground water, as it is used in this discussion, refers to any deterioration in the quality of the water resulting from the activities of man. This definition includes saltwater encroachment into freshwater-bearing aquifers resulting from the artificial lowering of ground-water heads. That topic, however, is covered in a separate discussion. (See "Saltwater Encroachment.")

Most pollution of ground water results from the disposal of wastes on the land surface, in shallow excavations including septic tanks, or through deep wells and mines; the use of fertilizers and other agricultural chemicals; leaks in sewers,

storage tanks, and pipelines; and animal feedlots. The magnitude of any pollution problem depends on the size of the area affected and the amount of the pollutant involved, the solubility, toxicity, and density of the pollutant, the mineral composition and hydraulic characteristics of the soils and rocks through which the pollutant moves, and the effect or potential effect on ground-water use.

Affected areas range in size from point sources, such as septic tanks, to large urban areas having leaky sewer systems and numerous municipal and industrial waste-disposal sites. Nearly all substances are soluble to some extent in water, and many chemical wastes are highly toxic even in minute concentrations. For example, table 1 lists the maximum concentrations of inorganic substances permitted in drinking-water supplies. Limits have also been established by the Environmental Protection Agency for radioactive and certain organic substances.

The density of a liquid substance—that is, the weight per unit volume of the substance relative to that of water—affects its underground movement. Densities range from those of petroleum products that are less dense than water to brines and other substances that are denser than water. Substances less dense than water tend to accumulate at the top of



GROUND-WATER POLLUTION OCCURS IN BOTH URBAN AND RURAL AREAS AND IS AFFECTED BY DIFFERENCES IN CHEMICAL COMPOSITION, BIOLOGICAL AND CHEMICAL REACTIONS, DENSITY, AND DISTANCE FROM DISCHARGE AREAS

the saturated zone; if, like petroleum, they are immiscible, they will tend to spread in all directions as a thin film. Substances denser than water tend to move downward through the saturated zone to the first extensive confining bed.

The mineral composition and physical characteristics of soils and rocks through which pollutants move may affect the pollutants in several ways. If a pollutant enters the ground at a "point," it will be dispersed longitudinally and laterally in granular materials so that its concentration will be reduced in the direction of movement. (See "Saturated Flow and Dispersion.") Organic substances and other biodegradable materials tend to be broken down both by oxidation and by bacterial action in the unsaturated zone. Certain earth materials, especially clays and organic matter, may also absorb trace metals and certain complex organic pollutants and thereby reduce their concentration as they move through the underground environment.

The hydraulic characteristics of the soils and rocks determine the path taken by and the rate of movement of pollutants. Substances dissolved in water move with the water except to the extent that they are tied up or delayed by adsorption. Thus, the movement of pollutants tends to be through the most permeable zones; the farther their point of origin from a ground-water discharge area, the deeper they penetrate into the ground-water system and the larger the area ultimately affected.

The factors related to the movement of pollutants discussed in the preceding paragraphs must be carefully considered in the selection of waste-disposal sites, animal feedlots,

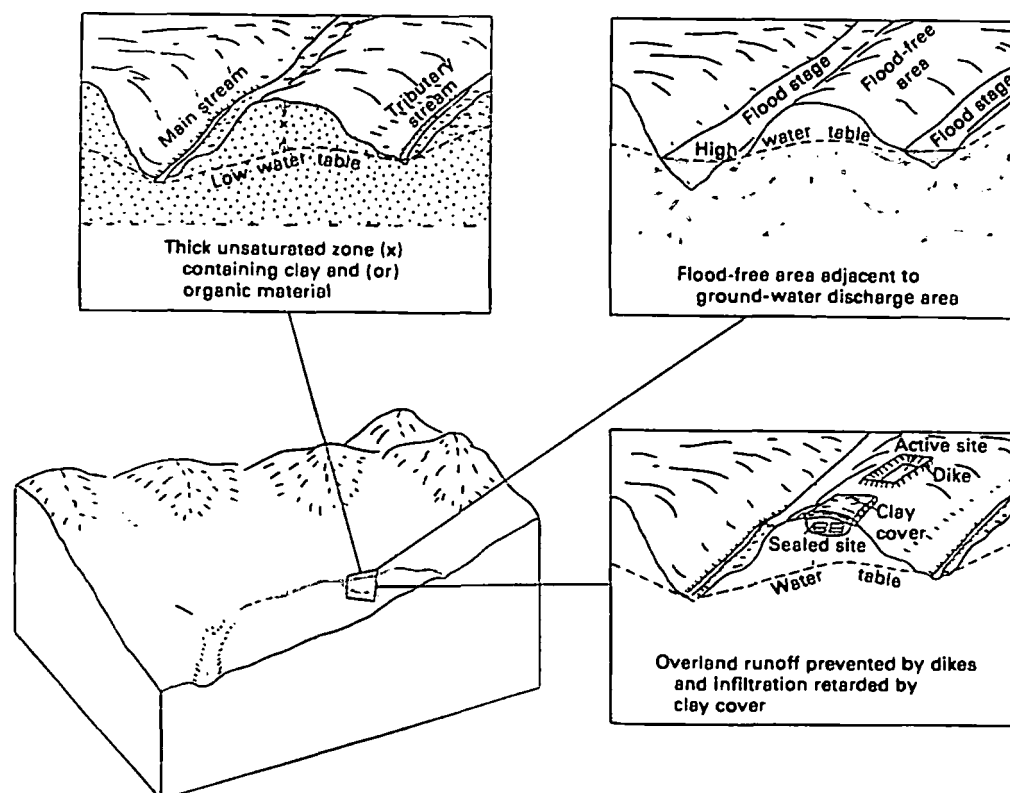
and sites for other operations that may cause ground-water pollution. With these factors in mind, it is obvious that significant ground-water pollution can be avoided only if waste-disposal sites are selected in such a way that:

1. Significant thicknesses of unsaturated material containing clay and (or) organic material are present.
2. Areas are as close as possible to places of natural ground-water discharge.
3. Overland runoff is excluded, and surface infiltration is held to the minimum possible amount.

Table 1. Maximum concentrations of inorganic constituents allowed in drinking water

[Data from U.S. Environmental Protection Agency (1977)]

Constituents	Concentration (mg/L)
Arsenic	0.05
Barium	1.
Cadmium	.010
Chromium	.05
Lead	.05
Mercury	.002
Nitrate (as N)	10.
Selenium	.01
Silver	.05



SELECTION OF WASTE-DISPOSAL SITES INVOLVES CONSIDERATION OF THE UNSATURATED ZONE, FLOOD DANGER, GROUND-WATER DISCHARGE, OVERLAND RUNOFF, AND INFILTRATION

SALTWATER ENCROACHMENT

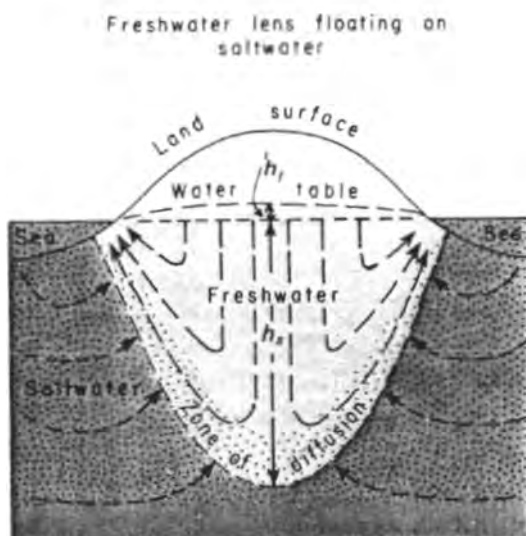
In coastal areas, fresh ground water derived from precipitation on the land comes in contact with and discharges into the sea or into estuaries containing brackish water. The relation between the freshwater and the seawater, or brackish water, is controlled primarily by the differences in their densities.

The density of a substance is its mass per unit volume; thus, the density of water is affected by the amount of minerals, such as common salt (NaCl), that the water contains in solution. In metric units, the density of freshwater is about 1 gm cm^{-3} , and the density of seawater is about 1.025 gm cm^{-3} . Thus, freshwater, being less dense than seawater, tends to override or float on seawater.

On islands, such as the Outer Banks of North Carolina, precipitation forms a freshwater lens that "floats" on the underlying saltwater (1). The higher the water table stands above sea level, the thicker the freshwater lens. This relation between the height of the water table and the thickness of the freshwater lens was discovered, independently, by a Dutchman, Badon Ghyben, and a German, B. Herzberg, and is referred to as the *Ghyben-Herzberg relationship*. This relation, expressed as an equation, is

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} (h_f) \quad (1)$$

where h_s is the depth of freshwater below sea level, ρ_f is the density of freshwater, ρ_s is the density of seawater, and h_f is the height of the water table above sea level.



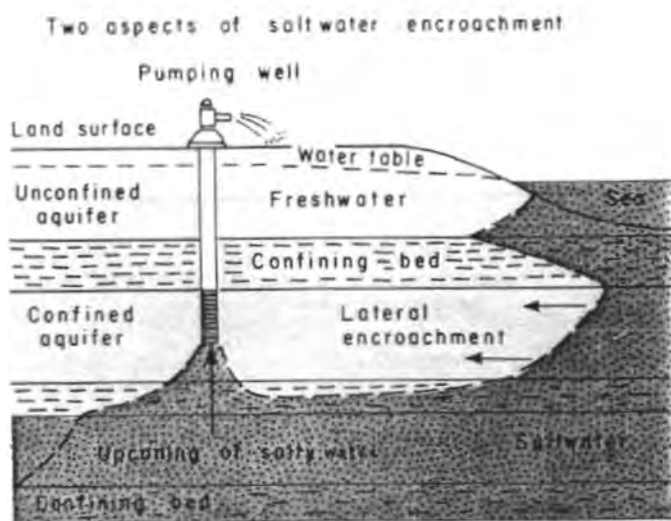
(1)

On the basis of equation 1 and the differences between the densities of freshwater and seawater, the freshwater zone should extend to a depth below sea level (h_s) equal to 40 times the height of the water table above sea level (h_f). The Ghyben-Herzberg relation applies strictly, however, only to a homogenous and isotropic aquifer in which the freshwater is static and is in contact with a tideless sea or body of brackish water.

Tides cause saltwater to alternately invade and retreat from the freshwater zone, the result being a zone of diffusion across which the salinity changes from that of freshwater to that of seawater (1). A part of the seawater that invades the freshwater zone is entrained in the freshwater and is flushed back to the sea by the freshwater as it moves to the sea to discharge.

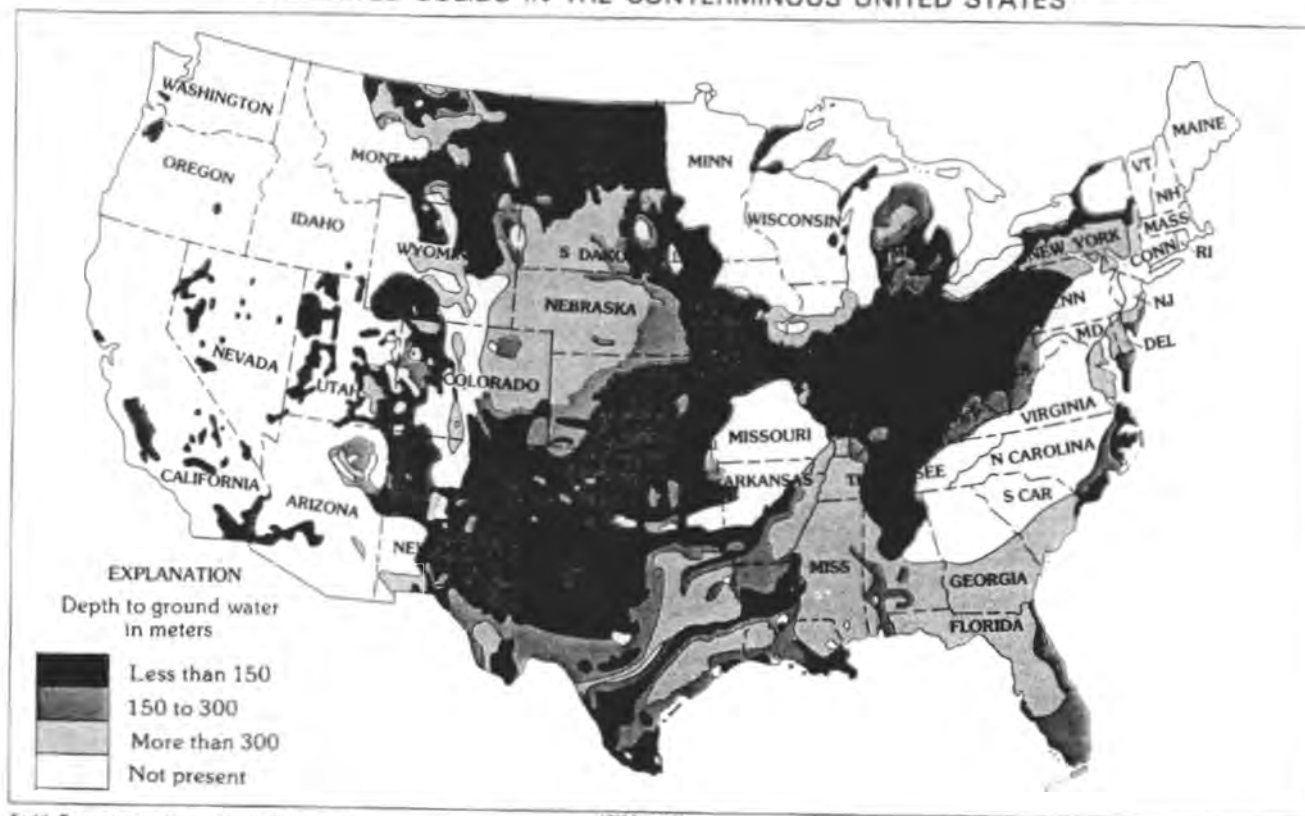
Because both the seawater and the freshwater are in motion (not static), the thickness of the freshwater zone in a homogenous and isotropic aquifer is greater than that predicted by the Ghyben-Herzberg equation. On the other hand, in a stratified aquifer (and nearly all aquifers are stratified), the thickness of the freshwater lens is less than that predicted because of the head loss incurred as the freshwater moves across the least permeable beds.

When freshwater heads are lowered by withdrawals through wells, the freshwater-saltwater contact migrates toward the point of withdrawals until a new balance is established (2). The movement of saltwater into zones previously occupied by freshwater is referred to as *saltwater encroachment*.

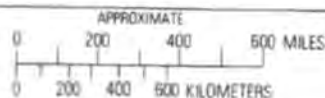


(2)

DEPTH TO GROUND WATER CONTAINING MORE THAN 1000 mg/L OF TOTAL DISSOLVED SOLIDS IN THE CONTERMINOUS UNITED STATES



Todd, Groundwater Hydrology, 2nd Ed., 1980



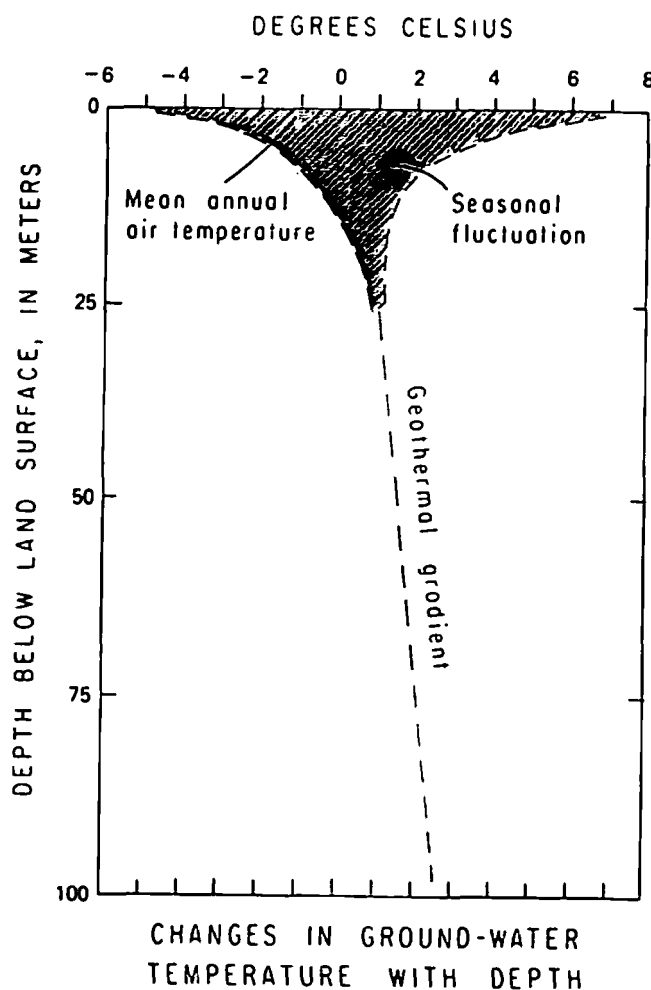
(3)

Saltwater encroachment is a serious problem in some coastal areas. Upconing of salty water beneath pumping wells is a more imminent problem than lateral encroachment in most areas. One reason is that lateral encroachment must displace a volume of freshwater much larger than that displaced by upconing. Another reason is that approximately two-thirds of the United States is underlain by aquifers that yield water containing more than 1,000 mg/L of total dissolved solids (3). (See table 2 in "Quality of Ground Water.") In most places, these aquifers are overlain by other aquifers that con-

tain freshwater and that serve as sources of water supply. However, where supply wells are drilled too deeply or are pumped at too large a rate, upconing of the mineralized (salty) water may occur.

In the design of supply wells in areas underlain by or adjacent to salty water, consideration must be given to the possibility of saltwater encroachment. This consideration may involve selection of shallow aquifers or small pumping rates to avoid upconing or involve moving wells to more inland locations to avoid lateral encroachment.

TEMPERATURE OF GROUND WATER



(1)

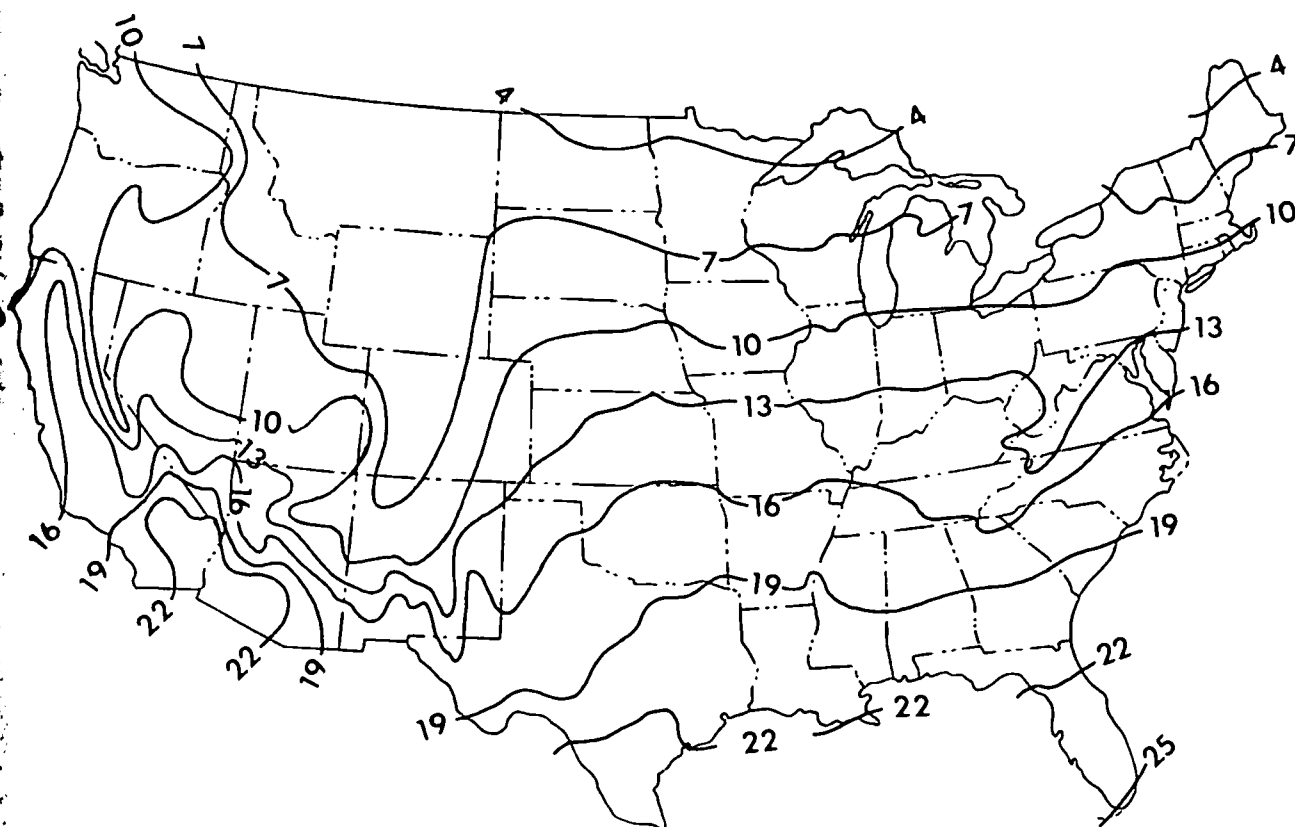
The temperature of ground water is one of its most useful characteristics. Ground water has been used for many years on Long Island, N.Y., and at other places as a heat-exchange medium for air-conditioning systems. As a result of recent increases in energy costs, ground water is also now becoming increasingly important as a source of heat for "heat pumps."

The temperature of ground water responds to seasonal variations in the heat received at the Earth's surface from the Sun and by movement of heat from the Earth's interior. The seasonal movement of heat into and out of the upper layers of the Earth's crust causes a seasonal fluctuation in ground-water temperatures to a depth of 10 to 25 m (1). The fluctuation is greatest near the surface, amounting to 5° to 10°C at depths of a few to several meters. In the zone affected by seasonal fluctuations, the mean annual ground-water temperature is 1° to 2°C higher than the mean annual air temperature (1). Consequently, a map showing the mean annual temperature of shallow ground water can be prepared on the basis of mean annual air temperature (sketch 2, based on a map showing mean annual air temperature prepared by the National Weather Service).

Movement of heat from the Earth's interior causes ground-water temperatures to increase with depth (1). This increase is referred to as the *geothermal gradient* and ranges from about 1.8°C per 100 m in areas underlain by thick sections of sedimentary rocks to about 3.6°C per 100 m in areas of recent volcanic activity. The effect of the geothermal gradient is not readily apparent in the zone affected by seasonal temperature fluctuations.

Movement of ground water causes a distortion in isotherms (lines depicting equal temperatures). This effect is most noticeable where ground-water withdrawal induces a movement of water from a stream into an aquifer. The distortion in ground-water temperature is most pronounced in the more permeable zones of the aquifer.

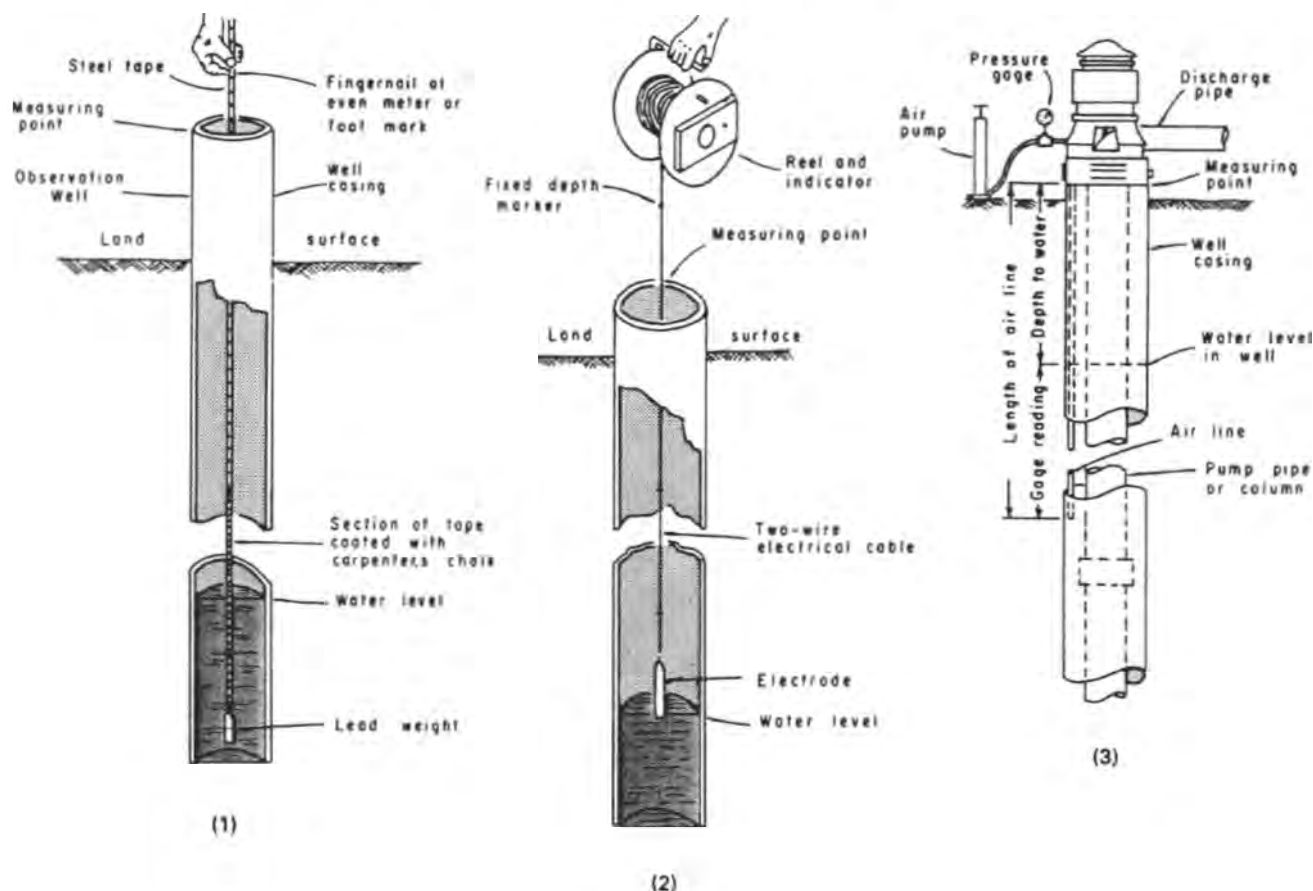
APPROXIMATE TEMPERATURE OF GROUND WATER, IN DEGREES CELSIUS, IN THE CONTERMINOUS
UNITED STATES AT DEPTHS OF 10 TO 25 M



(2)

MEASUREMENTS OF WATER LEVELS AND PUMPING RATES

METHODS FOR MEASURING THE DEPTH TO WATER LEVEL IN WELLS



Each supply well, regardless of whether it is used for domestic, irrigation, industrial, or public-supply needs, should be provided with a means for measuring the position of the water level in the well. Public-supply and industrial wells should also be provided with a means for measuring the pumping rate. The use of water-level and pumping-rate measurements is discussed in "Supply-Well Problems—Decline in Yield."

The first step in measuring the position of the water level is to identify (and describe) a fixed point—that is, a *measuring point*—to which all measurements will be referred. This point is usually the top of the casing, well cap, or access port. The three most common methods used in measuring the depth to water in wells are wetted tape, electric tape, and air line.

The *wetted-tape method* is probably the most common and most accurate of the three methods (1). This method utilizes a graduated steel tape with a weight attached to its end. The

graduations on the lower meter (3 to 4 ft) of the tape are coated with blue carpenter's chalk, and the tape is lowered into the well until the lower part of the tape is submerged and an even meter (or foot) mark is at the measuring point. The tape is then quickly withdrawn, and the value held at the measuring point and the amount of tape that was submerged are entered on a record form. The amount of tape that was submerged is obvious from the change in color of the chalk coating. The depth to the water level below the measuring point is determined by subtracting the length of wet tape from the total length of tape that was lowered into the well.

The *electric-tape method* involves an ammeter connected across a pair of insulated wires whose exposed ends are separated by an air gap in an electrode and containing, in the circuit, a source of power such as flashlight batteries (2). When the electrode contacts the water surface, a current flows through the system circuit and is indicated by a deflection of

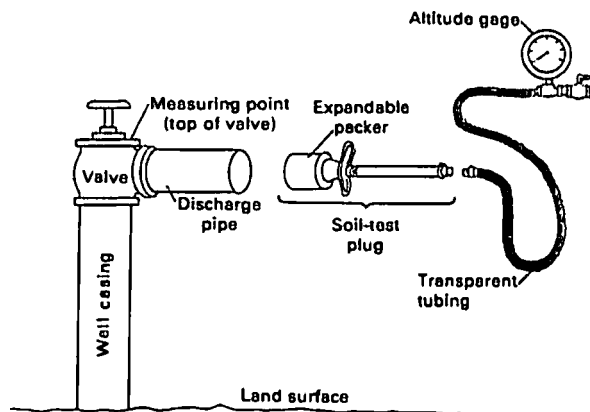
the ammeter needle. The insulated wires are marked at 1-m (or 5 ft) intervals. The nail of the index finger is placed on the insulated wires at the measuring point when the ammeter indicates that the circuit is closed. A steel tape or carpenter's rule is used to measure the distance from the point indicated by the fingernail to the next highest meter (or 5 ft) mark. This distance is subtracted from the value of the mark to determine the depth to water. One difference between the wetted-tape method and the electric-tape method is that, in the wetted-tape method, the subtraction involves the length of the submerged tape, whereas, in the electric-tape method, the subtraction involves the distance between the measuring point and the next highest mark.

The *air-line method* is generally used only in wells on which pumps are installed. This method involves the installation of a small-diameter pipe or tube (the air line) from the top of the well to a point about 3 m (10 ft) below the lowest anticipated position of the water level during extended pumping periods (3). The water level in this pipe is the same as that in the well. To determine the depth to water, an air pump and a pressure gage are attached to the top of the air line. Air is pumped into the line to force the water out of the lower end. As the water level in the air line is depressed, the pressure indicated by the gage increases. When all the water has been forced out of the line, the pressure-gage reading stabilizes and indicates the length of the water column originally in the air line. If the pressure-gage reading is subtracted from the length of the air line below the measuring point, which was carefully determined when the air line was installed, the remainder is the depth to water below the measuring point.

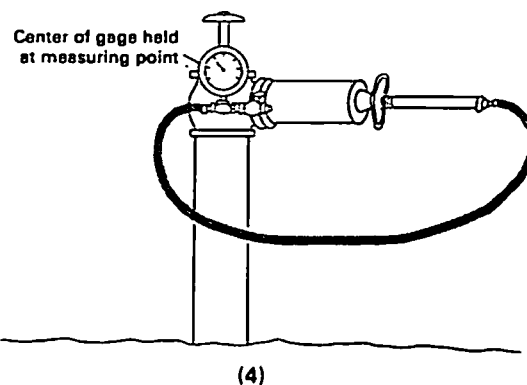
The preceding discussion has covered the measurement of water levels in nonflowing wells—that is, in wells in which the water level is below the measuring point. In many coastal areas and valleys underlain by confined aquifers, water levels in wells will stand at some height above the land surface. These areas are referred to as *areas of artesian flow*, and the measurement of water levels in wells, where casings have not been extended above the static level, may pose problems. If the well is equipped with a valve and a threaded fitting, the height of the water level can be determined by attaching the appropriate pipe connection and a pressure gage or transparent plastic tube.

Measuring the water level of flowing wells not equipped with a valve or a threaded fitting requires the use of soil-test plugs or some other device to control the flow. The position of the static water level above the measuring point is determined either with a pressure gage or with a plastic tube (4).

Components used to measure water pressure of flowing wells



Components installed for a pressure measurement

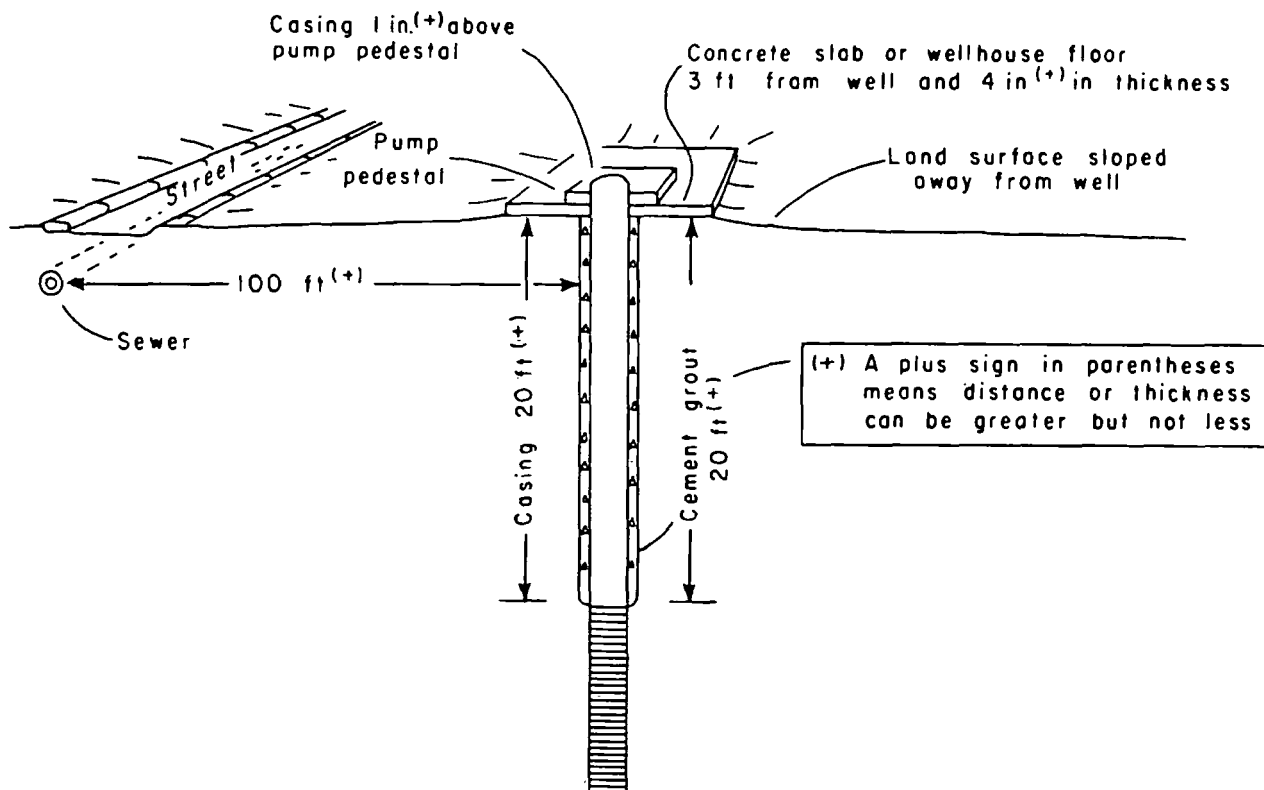


The measurement of the pumping rates of supply wells requires the installation of a flowmeter in the pump-discharge line. Either of two types of meters may be used, depending on the pumping rate. Up to a rate of about $1 \text{ m}^3 \text{ min}^{-1}$ (250 gal min^{-1}), an "active-element"-type meter may be used. These meters utilize either a propeller or a disk that is turned by the moving water. For larger pumping rates, meters that utilize a constriction in the discharge pipe are commonly used. These include venturi meters, flow nozzles, and orifices.

Flowmeters have dials that show either the total amount of water that has passed the meter or the rate at which the water is passing. With the first (the totalizing dial), the rate of discharge is determined by using a stopwatch to time the period for a certain volume of water to be pumped.

PROTECTION OF SUPPLY WELLS

TYPICAL REQUIREMENTS FOR SUPPLY WELLS



Most, if not all, States have laws related to the location and construction of public-supply wells. These laws and the rules and regulations developed for their administration and enforcement are concerned, among other things, with protecting supply wells from pollution. Pollution of the environment results from man's activities, and, consequently, except where deep wells or mines are used for waste disposal, it primarily affects the land surface, the soil zone, and the upper part of the saturated (ground water) zone. Therefore, the protection of supply wells includes avoiding areas that are presently polluted and sealing the wells in such a way as to prevent pollution in the future.

Fortunately, most ground-water pollution at the present time affects only relatively small areas that can be readily avoided in the selection of well sites. Among the areas in which at least shallow ground-water pollution should be expected are:

1. **Industrial districts** that include chemical, metalworking, petroleum-refining, and other industries that involve fluids other than cooling water.
2. **Residential areas** in which domestic wastes are disposed of through septic tanks and cesspools.
3. **Animal feedlots** and other areas in which large numbers of animals are kept in close confinement.
4. **Liquid and solid waste disposal sites**, including sanitary landfills, "evaporation ponds," sewage lagoons, and sites used for the disposal of sewage-plant effluent and solid wastes.
5. **Chemical stockpiles**, including those for salt used to deice streets and highways and for other chemical substances soluble in water.

In the selection of a well site, areas that should be avoided include not only those listed but also the zones surrounding them that may be polluted by movement of wastes in response to both the natural hydraulic gradient and the artificial gradient that will be developed by the supply well.

Rules and regulations intended to prevent future pollution include provision of "exclusion" zones around supply wells, requirements for casing and for sealing of the annular space, and sealing of the upper end of the wells.

Many State regulations require that supply wells be located at least 100 ft (30 m) from any sources or potential sources of pollution. In the case of public-supply wells, the well owner must either own or control the land within 100 ft (30 m) of the

well. In some States, a public-supply well may be located as close as 50 ft (15 m) to a sewer if the joints in the sewerline meet water-main standards.

Some State regulations require that all supply wells be cased to a depth of at least 20 ft (6 m) and that the annular space between the land surface and a depth of 20 ft (6 m) be completely filled with cement grout. The casing of supply wells drawing water from fractured bedrock must be seated and sealed into the top of the rock.

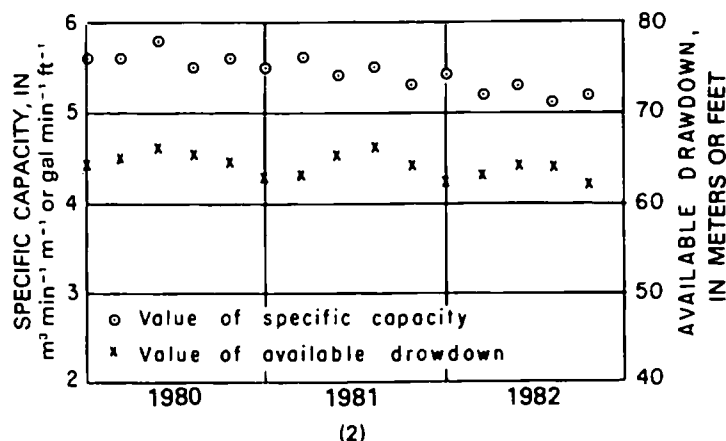
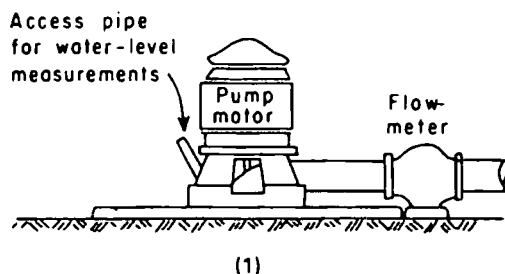
Most regulations require that the casing of all supply wells terminate above land surface and that the land surface at the site be graded or sloped so that surface water is diverted away from the well. Many States also require that public-supply wells have a continuous-bond concrete slab or concrete wellhouse floor at least 4 in. (10 cm) thick and extending at least 3 ft (1 m) horizontally around the outside of the well casing. The top of the well casing must project not less than 6 in. (15 cm) above the concrete slab or wellhouse floor. The top of the well casing must also project at least 1 in. (2.5 cm) above the pump pedestal. The top of the well casing must be sealed watertight except for a vent pipe or vent tube having a downward-diverted screened opening.

The regulations cited above provide, at best, only minimal protection for supply wells. There are numerous situations in which both the size of the exclusion zone and the depth of casing are inadequate. Relative to the radius of the exclusion zone, there are no arbitrary limits, except the physical boundaries of an aquifer, past which ground water cannot move. Relative to the minimum required casing, there are no vertical limits, except for the impermeable base of the ground-water system, past which polluted water cannot move.

On the other hand, there are geologic and hydrologic situations in which these regulations may be unnecessarily restrictive. An example is pollution in an unconfined aquifer down the hydraulic gradient from a supply well drawing from a deep confined aquifer overlain by a nonleaky confining bed.

Because of these factors, it is essential that officials involved in regulating the location and construction of supply wells be adequately trained in the fields of ground-water geology and hydrology so that they can protect the public health on the basis of scientific knowledge and technical judgment rather than that of blind application of arbitrary regulations.

SUPPLY-WELL PROBLEMS—DECLINE IN YIELD



The yield of any water-supply well depends on three elements: the aquifer, the well, and the pump. A decline in yield is due to a change in one of these elements, and correction of the problem depends on identification of the element that is involved. This identification in many cases can be made only if data are available on the depth to the water level in the well and the pumping rate. Inability to identify reasons for a decline in yield frequently results in discontinuing the use of ground water and developing more expensive supplies from surface-water sources.

The depth to the water level in a well equipped with a pump may be determined by using a steel tape, an electric tape, or an air line and pressure gage. The pumping rate of a supply well can be determined by any one of several different types of metering devices (1). (See "Measurements of Water Levels and Pumping Rates.")

The yield of a well depends on the drawdown and on the specific capacity. The specific capacity is the yield per unit of drawdown, and, in nearly all pumping wells, it varies with the pumping rate. Therefore, a discussion of decline in yield is meaningful only in terms of the maximum yield. The maximum yield of a well is controlled by the available drawdown and the specific capacity when the drawdown in the well equals the available drawdown. (See "Well-Acceptance Tests and Well Efficiency.")

The available drawdown is determined at the time of construction of a supply well and consists of the difference between the static (nonpumping) water level and the lowest practical pumping level. The lowest practical pumping level depends on the type of well. In screened wells, it is at the top of the uppermost screen. In open-hole fractured-rock wells, it is at the position of the lowest water-bearing fracture or at the lowest level at which the pump intake can be placed.

The specific capacity and the "yield" of supply wells are determined at the time of well construction. If the pumping level during the well-acceptance test is relatively close (within a few meters) to the lowest practical level, the specific capacity determined during the test can be used to accurately estimate the maximum yield. However, it is important to note that apparent declines in yield after wells are placed in production reflect, in many cases, overestimation of the yields at the time of construction. Actual declines in yield after wells are placed in operation result from deterioration of pumps, declines in the static water level or the specific capacity, or combinations of all three.

The yield of a well field is the sum of the yields of the individual wells. Successful operation, therefore, requires periodic measurements of both the specific capacity and the available drawdown for each well. Changes in these values are used to predict the yield of the field at different times in the future and, when they are used in conjunction with predictions of needs, to plan the rehabilitation of existing wells or the construction of new wells.

Measurements of specific capacity and available drawdown are neither difficult nor time consuming. The determination of both requires only the three measurements listed below:

1. Static (nonpumping) water level (w. l.), measured weekly near the end of the longest nonpumping period, which, in most systems with large industrial uses, is near the end of the weekend.
2. Maximum pumping water level, measured weekly near the end of the longest period of continuous use, which, in most water systems, is near the end of the workweek.
3. Pumping rate, measured at the same time as the maximum pumping water level.

These three items of data are analyzed as follows to determine the maximum yield of the well.

specific capacity

$$= \frac{\text{pumping rate (m}^3 \text{ min}^{-1} \text{ or gal min}^{-1})}{\text{static w. l. (m or ft) - pumping w. l. (m or ft)}}$$

$$= \frac{\text{m}^3}{\text{min m}} \text{ or } \frac{\text{gal}}{\text{min ft}}$$

available drawdown (m or ft)

$$= (\text{static water level, in m or ft}) - (\text{lowest practical water level, in m or ft})$$

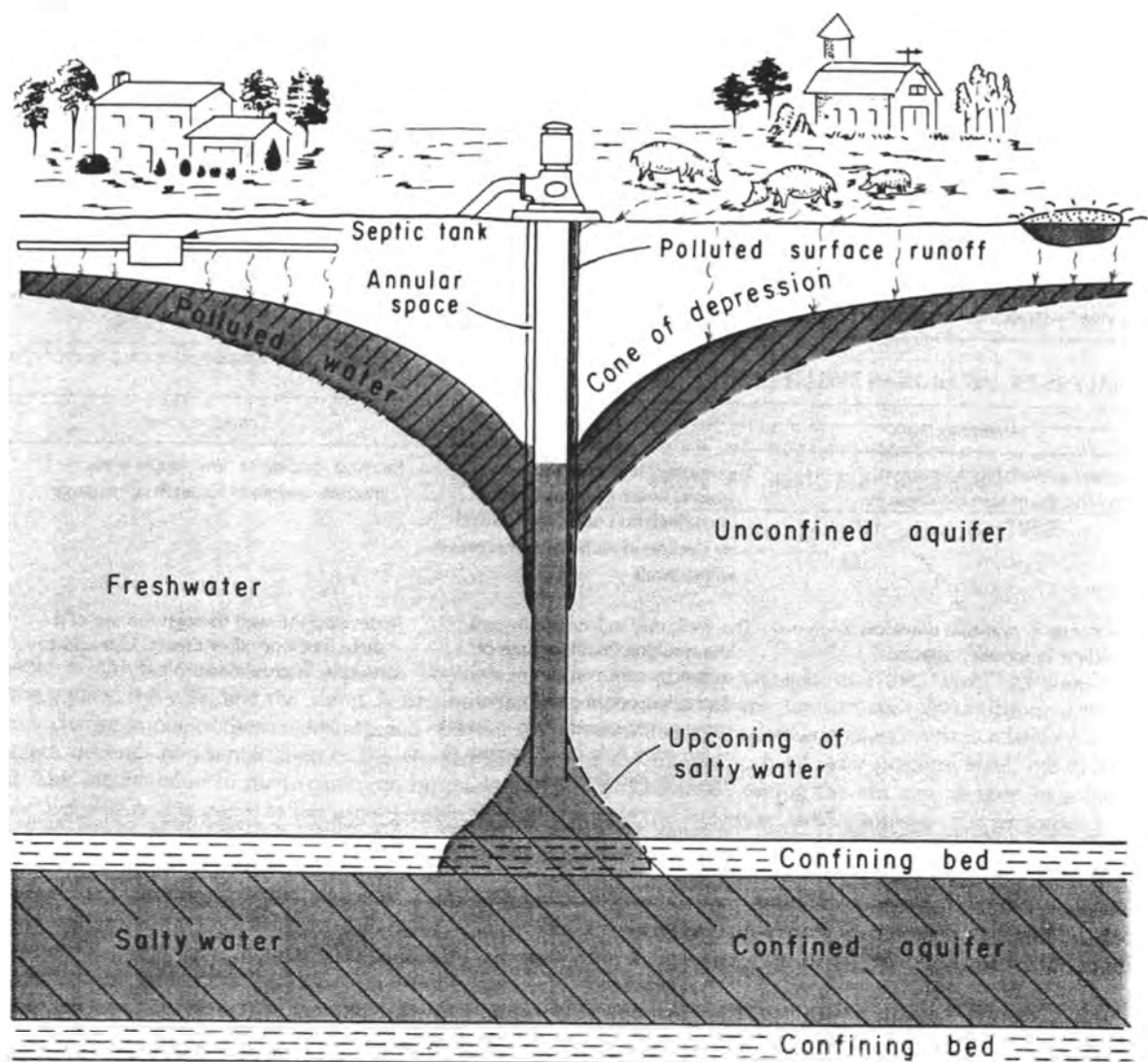
$$\text{maximum yield} = (\text{specific capacity}) \times (\text{available drawdown})$$

Determinations of specific capacity and available drawdown should be carefully preserved as a part of the permanent file on each well. (See "Well Records and Files.") They should be analyzed at least quarterly to determine if changes in either are occurring. This analysis can be done most conveniently if the values are plotted on graph paper versus the time of the determination (2). Changes in available drawdown and (or) specific capacity and suggested causes and corrective action are listed in the accompanying table.

ANALYSIS OF DECLINES IN WELL YIELD

Identifying criteria	Cause	Corrective action
Decline in available drawdown, ----- no change in specific capacity.	The aquifer, due to a decline in ground-water level resulting from depletion of storage caused by decline in recharge or excessive withdrawals.	Increase spacing of new supply wells. Institute measures for artificial recharge.
No change in available drawdown, ----- decline in specific capacity.	The well, due to increase in well loss resulting from blockage of screen by rock particles or by deposition of carbonate or iron compounds; or reduction in length of the open hole by movement of sediment into the well.	Redevelop the well through the use of a surge block or other means. Use acid to dissolve encrustations.
No change in available drawdown, ----- no change in specific capacity.	The pump, due to wear of impellers and other moving parts or loss of power from the motor.	Recondition or replace motor, or pull pump and replace worn or damaged parts.

SUPPLY-WELL PROBLEMS—CHANGES IN WATER QUALITY



The problems most frequently encountered in the operation of supply wells relate either to declines in yield or to deterioration in the quality of the water. Declines in yield are discussed in "Supply-Well Problems—Decline in Yield."

Deterioration in water quality may result either from changes in the quality of water in the aquifer or changes in the well. These changes may affect the biological quality, the chemical quality, or the physical quality. Deterioration in biological and chemical quality generally results from conditions in the aquifer, whereas changes in physical quality result from changes in the well.

Both the biological and the chemical quality of water from new public-supply wells must be analyzed before the wells are placed in use to determine if the water meets water-supply standards and, if it does not, what treatment is required. Drinking-water regulations of the U.S. Environmental Protection Agency also require that analyses of biological quality be

made monthly and that analyses of inorganic quality be made at least every 3 years for all community systems supplied entirely by ground water. It is good practice to periodically determine the biological and chemical quality of water from all wells, especially those that supply domestic needs, in order to determine if changes in quality are occurring.

Deterioration in *biological quality* refers to the appearance in the water of bacteria and (or) viruses associated with human or animal wastes. Such deterioration is referred to under the general term *pollution* and indicates, in nearly all cases, a connection between the land surface or a near-surface zone and the open section of the well. The connection most frequently exists in the annular space between the casing and the aquifer. To avoid pollution of wells, many well-construction regulations require that the annular space be completely filled with cement grout from the land surface to a depth of at least 20 ft (6 m).

Deterioration in chemical quality refers to the arrival at a supply well of water containing dissolved chemicals in an undesirably large concentration. Withdrawals of water from a well cause water to converge on the well from different directions. If this convergence involves water containing a large concentration of any substance, the concentration of that substance will, after some period of time, begin to increase. The most commonly observed increases in concentration involve NaCl (sodium chloride or common salt) and NO₃ (nitrate), but, if the well is near a sanitary landfill or other waste-disposal site, the increase may involve almost any substance commonly used by man.

Nitrate is an important constituent in fertilizers and is present in relatively large concentrations in human and animal wastes. Therefore, nitrate concentrations in excess of a few milligrams per liter almost invariably indicate that water is arriving at the well from shallow aquifers that are polluted by septic tanks or animal feedlots or that are contaminated by excess nitrates used in farming operations.

Sodium chloride is the principal constituent of seawater and is also present in significant concentrations in human and animal wastes and in some industrial wastes. An increase in the chloride content in well water most commonly indicates upward movement of water from an underlying zone of salty water. Other increases are due to pollution by sources at or near the land surface, such as deicing operations on streets and highways in the northern part of the country.

Although increases in chloride and nitrate content are probably the most common changes in chemical quality that occur in ground water, changes may involve almost any sub-

stance soluble in water. Thus, it is important to be aware of the accidental or intentional release of potential pollutants within the area of influence of all supply wells. Substances that are of particular concern in this regard include herbicides, pesticides and other complex organics, petroleum products, and those substances that contain trace concentrations of metals. In planning a sampling program, for these substances or any others, it is important to consider the slow rate at which most ground water moves.

Deterioration in physical quality involves changes in appearance, taste, and temperature. Most commonly, a change in appearance or color involves either the gradual or the sudden appearance of rock particles in the water. These particles can range in size from clay, which gives the water a turbid or "bluish" appearance, to sand. The size of the particles is indicated by the rate at which the particles settle. If the particles settle exceedingly slowly, or not at all, they are clay size. If they settle immediately, they are sand size.

The gradual appearance of particles generally indicates that the finer grained material was not adequately removed from the zone adjacent to the well during well development. (See "Well-Construction Methods.") During use of the well, these particles slowly migrate to and into the well. The sudden appearance of particles—that is, when the concentration of particles is large (very obvious) from the beginning—generally indicates the failure (collapse) of the screen or a rupture of the well casing.

Changes in the quality of water produced by a well, likely causes of the change, and suggested corrective action are listed in the accompanying table.

ANALYSIS OF CHANGES IN WATER QUALITY

Change in quality	Cause of the change	Corrective action
Biological -----	Movement of polluted water from the surface or near-surface layers through the annular space.	Seal annular space with cement grout or other impermeable material and mound dirt around the well to deflect surface runoff.
Chemical -----	Movement of polluted water into the well from the land surface or from shallow aquifers.	Seal the annular space. If sealing does not eliminate pollution, extend the casing to a deeper level (by telescoping and grouting a smaller diameter casing inside the original casing).
	Upward movement of water from zones of salty water.	Reduce the pumping rate and (or) seal the lower part of the well.
Physical -----	Migration of rock particles into the well through the screen or from water-bearing fractures penetrated by open-hole wells.	Remove pump and redevelop the well
	Collapse of the well screen or rupture of the well casing.	Remove screen, if possible, and install new screen. Install smaller diameter casing inside the original casing.

WELL RECORDS AND FILES

The collection and preservation of records on the construction, operation, maintenance, and abandonment of supply wells are an essential but largely neglected activity. This responsibility rests largely on the well owner or operator. The consequence of this neglect is that it is not possible to identify and to economically correct problems of declining yield or deterioration in water quality, and the design of new wells cannot incorporate past operational experience.

A file should be established on each supply well at the time when plans for its construction are initiated. From the initial planning to the final abandonment of the well, the following records should be generated and carefully preserved in this file:

1. **Initial design**, including drawings or written specifications on diameter, proposed total depth, position of screens or open hole, method of construction, and materials to be used in construction. (See "Water-Well Design.")
2. **Construction record**, including the method of construction and the driller's log and a geophysical log of the materials penetrated during construction, the diameter of casings and screens, the slot size and metallic composition of screens, the depths of casing and screens, the total depth of the well, and the weight of the casing. (See "Well-Construction Methods" and "Well Logs.") Records and logs should also be retained for all test wells, including those that were not successful because of small yields.
3. **Well-acceptance test**, including a copy of the water-level measurements made before, during, and after the drawdown (pumping) test, a record of the pumping rate or rates, copies of any graphs of the data, and a copy of the hydrologist's report on the interpretation of the test results. (See "Well-Acceptance Tests and Well Efficiency.")
4. **Pump and installation data**, including the type of pump, the horsepower of the motor, the depth to the pump intake, a copy of the pump manufacturer's performance and efficiency data, and data on the length of the air line or a description of facilities provided for water-level measurements, including a description of the measuring point. (See "Measurements of Water Levels and Pumping Rates.")
5. **Operating record**, including data on the type of meter used to measure the flow rate, weekly readings of the flow-meter dial, weekly measurements of the static and pumping water levels, and periodic analyses of water quality. (See "Supply-Well Problems—Decline in Yield.")
6. **Record of well maintenance**, including the dates and the activities instituted to increase the yield or to improve the water quality and data showing the results achieved. (See "Supply-Well Problems—Decline in Yield" and "Supply-Well Problems—Changes in Water Quality.")
7. **Record of well abandonment**, including the date that use of the well was discontinued and a description of the methods and materials used to seal or plug the well.

The type of forms used for the records described above is not of critical importance. It is more important that the records be collected, regardless of the type of form that is used. It is important, however, that the date and the watch time be noted with each measurement of pumping rate and depth to water and on each water sample collected for water-quality analyses.

REFERENCES

A large number of publications on ground-water hydrology were consulted in the preparation of this report. A citation is shown in the text only where a publication was used as a specific source of tabular data.

The following list of principal references consulted is included to identify sources of specific information and for the benefit of those who wish to obtain additional information.

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NUMBERS, EQUATIONS, AND CONVERSIONS

The preceding discussions of basic ground-water hydrology involve the use of equations and physical units with which some readers may not be familiar. This discussion of numbers, equations, and conversion of units from one system of measurement to another is included for the benefit of those readers and for others who need to refresh their memories.

Expressing Large Numbers

$$1,000 = 10 \times 10 \times 10 = 1 \times 10^3$$

$$1,000,000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1 \times 10^6$$

The numbers 3 and 6 are called exponents and indicate the number of times that 10 must be multiplied by itself to obtain the initial number.

Expressing Small Numbers

$$0.001 = \frac{1}{1,000} = \frac{1}{1 \times 10^3} = 1 \times 10^{-3}$$

$$0.000001 = \frac{1}{1,000,000} = \frac{1}{1 \times 10^6} = 1 \times 10^{-6}$$

Exponents in the denominator acquire a negative sign when they are moved to the numerator.

Simplifying Equations

Symbols in equations have numerical values and, in most cases, units of measurement, such as meters and feet, in which the values are expressed. For example, Darcy's law, one of the equations used in basic ground-water hydrology, is

$$Q = KA \left(\frac{dh}{dl} \right)$$

In metric units, hydraulic conductivity (K) is in meters per day, area (A) is in square meters, and hydraulic gradient (dh/dl) is in meters per meter. Substituting these units in Darcy's law, we obtain

$$Q = \frac{\text{meters}}{\text{day}} \times \text{meters}^2 \times \frac{\text{meters}}{\text{meters}} = \frac{\text{meters}^3}{\text{meters day}} = \text{m}^2 \text{ d}^{-1} = \text{m}^3 \text{ d}^{-1}$$

Similarly, in inch-pound units, K is in feet per day, A is in square feet, and dh/dl is in feet per feet. Substituting these units in Darcy's law, we obtain

$$Q = \frac{\text{feet}}{\text{day}} \times \text{feet}^2 \times \frac{\text{feet}}{\text{feet}} = \frac{\text{feet}^3}{\text{feet day}} = \text{ft}^2 \text{ d}^{-1} = \text{ft}^3 \text{ d}^{-1}$$

The characteristics of exponents are the same, whether they are used with numbers or with units of measurement. Exponents assigned to units of measurement are understood to apply, of course, to the value that the unit of measurement has in a specific problem.

Conversion of Units

Units of measurements used in ground-water literature are gradually changing from the inch-pound units of gallons, feet, and pounds to the International System of units of meters and kilograms (metric units). It is, therefore, increasingly important that those who use this literature become proficient in converting units of measurement from one system to another. Most conversions involve the fundamental principle that the numerator and denominator of a fraction can be multiplied by the same number (in essence, multiplying the fraction by 1) without changing the value of the fraction. For example, if both the numerator and the denominator of the fraction $1/4$ are multiplied by 2, the value of the fraction is not changed. Thus,

$$\frac{1}{4} \times \frac{2}{2} = \frac{2}{8} = \frac{1}{4} \quad \text{or} \quad \frac{1}{4} \times \frac{2}{2} = \frac{1}{4} \times 1 = \frac{1}{4}$$

Similarly, to convert gallons per minute to other units of measurement, such as cubic feet per day, we must first identify fractions that contain both the units of time (minutes and days) and the units of volume (gallons and cubic feet) and that, when they are used as multipliers, do not change the numerical value. Relative to time, there are 1,440 minutes in a day. Therefore, if any number is multiplied by $1,440 \text{ min/d}$, the result will be in different units, but its numerical value will be unchanged. Relative to volume, there are 7.48 gallons in a cubic foot. Therefore, to convert gallons per minute to cubic feet per day, we multiply by these "unit" fractions, cancel the units of measurement that appear in both the numerator and the denominator, and gather together the units that remain. In other words, to convert gallons per minute to cubic feet per day, we have

$$\frac{\text{gallons}}{\text{minute}} = \frac{\text{gallons}}{\text{minute}} \times \frac{1,440 \text{ min}}{\text{d}} \times \frac{\text{cubic feet}}{7.48 \text{ gal}}$$

and, canceling gallons and minutes in the numerators and denominators, we obtain

$$\frac{\text{gallons}}{\text{minute}} = \frac{1,440 \text{ ft}^3}{7.48 \text{ d}} = 192.5 \text{ ft}^3 \text{ d}^{-1}$$

which tells us that 1 gal min^{-1} equals $192.5 \text{ ft}^3 \text{ d}^{-1}$.

We follow the same procedure in converting from inch-pound units to metric units. For example, to convert square feet per day to square meters per day, we proceed as follows:

$$\frac{\text{ft}^2}{\text{d}} = \frac{\text{ft}^2}{\text{d}} \times \frac{\text{m}^2}{10.76 \text{ ft}^2} = \frac{\text{m}^2}{10.76 \text{ d}} = 0.0929 \text{ m}^2 \text{ d}^{-1} = 9.29 \times 10^{-2} \text{ m}^2 \text{ d}^{-1}$$

RELATION OF UNITS OF HYDRAULIC CONDUCTIVITY, TRANSMISSIVITY, RECHARGE RATES, AND FLOW RATES

Hydraulic conductivity (K)

Meters per day (m d ⁻¹)	Centimeters per second (cm s ⁻¹)	Feet per day (ft d ⁻¹)	Gallons per day per square foot (gal d ⁻¹ ft ⁻²)
1	1.16 × 10 ⁻³	3.28	2.45 × 10 ¹
8.64 × 10 ²	1	2.83 × 10 ³	2.12 × 10 ⁴
3.05 × 10 ⁻¹	3.53 × 10 ⁻⁴	1	7.48
4.1 × 10 ⁻²	4.73 × 10 ⁻⁵	1.34 × 10 ⁻¹	1

Transmissivity (T)

Square meters per day (m ² d ⁻¹)	Square feet per day (ft ² d ⁻¹)	Gallons per day per foot (gal d ⁻¹ ft ⁻¹)
1	10.76	80.5
.0929	1	7.48
.0124	.134	1

Recharge rates

Unit depth per year	(m ³ d ⁻¹ km ⁻²)	Volume (ft ³ d ⁻¹ mi ⁻²)	(gal d ⁻¹ mi ⁻²)
(In millimeters)	2.7	251	1,874
(In inches)	70	6,365	47,748

Flow rates

(m ³ s ⁻¹)	(m ³ min ⁻¹)	(ft ³ s ⁻¹)	(ft ³ min ⁻¹)	(gal min ⁻¹)
1	60	35.3	2,120	15,800
.0167	1	.588	35.3	264
.0283	1.70	1	60	449
.000472	.0283	.0167	1	7.48
.000063	.00379	.0023	.134	1

UNITS AND CONVERSIONS

Metric to inch-pound units

LENGTH

1 millimeter (mm) = 0.001 m = 0.03937 in.
 1 centimeter (cm) = 0.01 m = 0.3937 in. = 0.0328 ft
 1 meter (m) = 39.37 in. = 3.28 ft = 1.09 yd
 1 kilometer (km) = 1,000 m = 0.62 mi

AREA

1 cm² = 0.155 in.²
 1 m² = 10.758 ft² = 1.196 yd²
 1 km² = 247 acres = 0.386 mi²

VOLUME

1 cm³ = 0.061 in.³
 1 m³ = 1,000 l = 264 U.S. gal = 35.314 ft³
 1 liter (l) = 1,000 cm³ = 0.264 U.S. gal

MASS

1 microgram (μg) = 0.000001 g
 1 milligram (mg) = 0.001 g
 1 gram (g) = 0.03527 oz = 0.002205 lb
 1 kilogram (kg) = 1,000 g = 2.205 lb

Inch-pound to metric units

LENGTH

1 inch (in.) = 25.4 mm = 2.54 cm = 0.0254 m
 1 foot (ft) = 12 in. = 30.48 cm = 0.3048 m
 1 yard (yd) = 3 ft = 0.9144 m = 0.0009144 km
 1 mile (mi) = 5,280 ft = 1.609 m = 1.609 km

AREA

1 in.² = 6.4516 cm²
 1 ft² = 929 cm² = 0.0929 m²
 1 mi² = 2.59 km²

VOLUME

1 in.³ = 0.00058 ft³ = 16.39 cm³
 1 ft³ = 1728 in.³ = 0.02832 m³
 1 gallon (gal) = 231 in.³ = 0.13368 ft³ = 0.00379 m³

MASS

1 ounce (oz) = 0.0625 lb = 28.35 g
 1 pound (lb) = 16 oz = 0.4536 kg

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**UNITED STATES
ENVIRONMENTAL PROTECTION
AGENCY**



REGION VIII

GROUNDWATER PROGRAM UNIT

QUALITY ASSURANCE PROJECT PLAN

**GROUNDWATER PROTECTION PROGRAM
UNDERGROUND INJECTION CONTROL PROGRAM
UNDERGROUND STORAGE TANK PROGRAM**

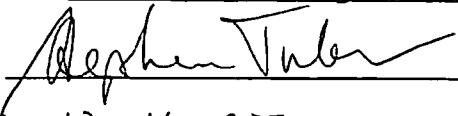
Preface

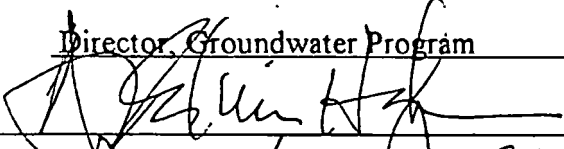
This version of the EPA Region VIII Groundwater Program Quality Assurance Project Plan (December, 1997) reflects the current technical guidance, procedures, and quality assurance goals of the Region VIII Quality Management Plan. This document requires periodic review and updating as new technical procedures and regional quality assurance goals are developed, or as deemed necessary by Groundwater Program Director.

Questions regarding the contents and preparation of this document can be directed to the following person:

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Approval Page

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Date 12-4-97

Name D. Edwin Hogle
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Signature 
Date December 3, 1997

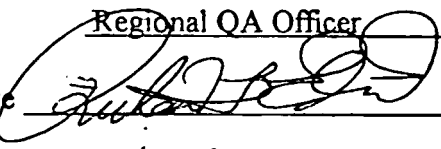
Name Richard L. Edmonds
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Signature 
Date 12/10/97

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Distribution List

In order to maintain an effective Quality Assurance/Quality Control program that is user friendly and reflective of how Groundwater Program project work is conducted, it is essential that this QAPP be kept current and that all Groundwater Program personnel involved in the work effort have a current version of this document on hand for reference and guidance.

The current EPA Region 8 Groundwater Program QAPP is being distributed to the following personnel:

Terry Bahrych	8P2-W-GW	Lisa Luebke	8P2-W-GW
Bob Becker	8P2-W-GW	Dean McKinnis	8P2 SA
Arnold Boettcher	8MO	Douglas Minter	8P2-W-GW
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Purpose

Any project that generates environmental data in support of programs under the direction of U.S. Environmental Protection Agency (EPA) is required to develop and follow a Quality Assurance Project Plan (QAPP) containing quality assurance and quality control procedures. In addition, data collection activities must be performed in accordance with the requirements of the approved QAPP.

This QAPP was created so that EPA decision-makers are provided with sufficient knowledge concerning the quality of the data generated under the Groundwater Program Unit. This document is a tool to be used in the planning process to reduce the risk of the user making an incorrect decision based on environmental data generated by Groundwater Program field investigations. This risk is different from the "human health risk" often associated with environmental decisions. In this case, "risk" refers to the consequences of wrong decisions in terms of adverse environmental impact, added time, and increased cost. This QAPP also provides a guideline for developing a method of evaluating data useability.

This QAPP is designed to ensure that all Groundwater Program data collection activities are conducted in a manner that: (1) ensures the integrity of the data; (2) provides EPA the best opportunity to make data-dependent decisions; and (3) allows EPA to fully enforce and defend its position on any compliance issue.

Introduction

This QAPP provides a blueprint of how quality assurance and quality control are applied in Groundwater Program data collection activities to assure that the results obtained are of the type and quality needed and expected. The concepts involved are defined below.

Data Quality Objectives (DQOs)

Data quality objectives are quantitative and qualitative statements specifying the quality of data needed to meet the goals of the data collection effort. Data quality is defined in terms of data indicators including accuracy, precision, representativeness, comparability, and completeness. The planning process for ensuring environmental data are of the type, quantity, and quality needed for decision-making is the DQO process. The DQO process should be the first step in any data collection activity and lays the ground work for the Quality Assurance and Quality Control requirements for the data collection effort. The DQO process will not be addressed in this document, but can be found in "Plan for Data Collection Using the DQO Process" (EPA QA/G-4); "Collecting Environmental Data Using Documented Sampling Schemes" (EPA QA/G-5); and "Conducting Data Quality Assessment" (EPA QA/G-9).

Quality Assurance (QA)

Quality Assurance is a management system governing data collection activities that includes planning, quality control, implementation, quality assessment, documentation, and quality improvement. QA provides the information needed to determine whether the data meets the DQOs of the data collection effort. Developing and implementing a QA system will ensure that data will meet defined standards of quality with a stated level of confidence.

Quality Control (QC)

Quality Control is the overall system of routine technical activities that compares performance against defined standards to verify that the intended quality assurance requirements are met. QC is a system to identify and control errors in sample collection, handling, and analysis, or other data gathering processes.

This QAPP addresses the QA and QC requirements for data collection activities performed within the Groundwater Program Unit in EPA Region VIII. The data collection activities outlined within this document are intended to cover investigations of suspected contamination performed by all programs under the Groundwater Program Unit and may involve collection of samples from different types of matrices including soil, air, ground water, surface water, and solids/sludge. The procedures and methods outlined in this QAPP are the minimum requirements under which the program specific Standard Operating Procedures (SOPs) have been developed for each program within the Groundwater Unit. Existing SOPs developed by other programs have been adopted where applicable. SOPs present the required procedures for the specific field and sampling activities conducted during routine Groundwater Program field investigations. A site specific Sampling and Analysis Plan (SAP) must be developed for any field data collection activity undertaken in the Groundwater Program (activities conducted under financial assistance agreements are beyond the scope of this document). The SAP describes the purpose of the sampling event, the sampling method, sample handling procedures, analytical procedures, and the QA/QC aspects of sampling. The SAP addresses QA/QC concerns in a very site-specific manner, supplementing this generalized QAPP which is intended as a summary of minimum requirements for assembling the QA/QC sections of the SAP. For routine field investigations, a SAP will reference the SOPs for each program. It must be noted that a SAP must also go through an official approval process that involves the EPA staff person performing the work and his/her immediate supervisor.

As with any data-gathering event, there will be situations where changes to the procedures listed in this QAPP are required due to uncontrolled situations either in the field or in the laboratory. For these cases, any changes to the procedures listed in this QAPP must be documented, explaining the reasons for the change. This explanation shall be included within the SAP or the field notes or inspection report as appropriate.

Project/Task Organization

The Groundwater Unit is a group within the Pollution Prevention, State and Tribal Assistance Program under the Water Program. The hierarchy of programs is illustrated in the organizational chart shown in Figure 1.

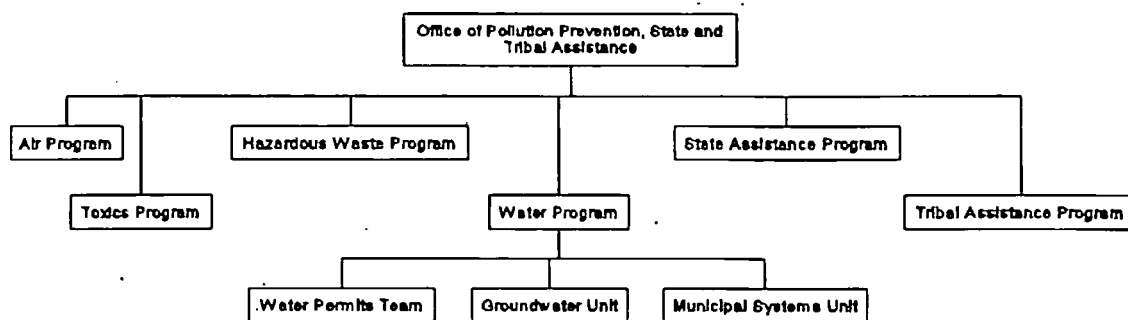


Figure 1. Office of Pollution Prevention, State and Tribal Assistance Program Organizational Chart

The Groundwater Unit includes three programs, the Groundwater Protection Program, Underground Injection Control Program, and the Underground Storage Tank/Leaking Underground Storage Tank Program, which deal with the protection, evaluation, and remediation of ground water for present and potential future sources of drinking water. The relationship of these programs within the programmatic hierarchy is shown in Figure 2.

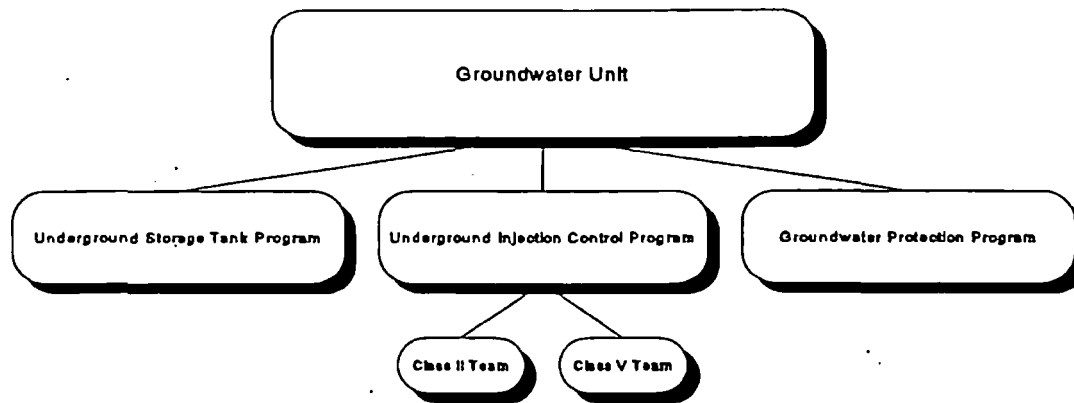


Figure 2. Organizational Chart for the Groundwater Unit

Problem Definition/Background

The programs under the Groundwater Unit are tasked with determining compliance with the following environmental statutes and associated regulations and guidance:

Resource Conservation and Recovery Act, Subtitle I

Safe Drinking Water Act, Part C - Protection of Underground Sources of Drinking Water

The Clean Water Act

Groundwater Protection Program

The Groundwater Protection Program was established to provide a framework for a Federal/State partnership to protect ground water resources. Under this partnership the States have primary responsibility for protecting and managing ground water. EPA is responsible for regulating specific contaminants and sources of contamination and providing technical and financial support to the States. EPA's Groundwater Protection strategy has four major objectives:

- To build and enhance ground water protection programs at the State level;
- To expand controls where appropriate over currently uncontrolled sources of contamination;
- To achieve greater consistency in EPA decisions on ground water protection and clean up; and
- To strengthen EPA's nationwide organization for ground water protection.

Underground Injection Control Program

The Underground Injection Control (UIC) Program was established to prevent contamination of underground sources of drinking water (USDWs) that can result from the operation and abandonment of injection wells. Because injection well practices vary considerably, the means by which an USDW can become contaminated also vary. Listed below are the most common potential routes of USDW contamination by each well type..

Class I, II, and III: These wells are used primarily for the deep disposal of industrial waste fluids, the recovery or enhanced recovery of oil and gas or mineral resources, or for disposal of fluids produced as a result of oil and gas production operations. Contamination of USDWs most commonly occurs due to a leak in the well tubing, packer, or casing, fracturing of the confining zones(s) that surround the injection zone, inadequate cementation of the casing of the wellbore, or migration of waste fluid out of the injection formation through abandoned and/or inadequately constructed wells.

Class V: The Region VIII Class V program is at this time primarily concerned with shallow injection wells at industrial facilities (including automotive, machine shops, metal plating, electronics, and photographic processing) that are known to dispose of potentially hazardous waste fluids into or above USDWs. Contamination can occur when these industrial facilities dispose of wastes (such as heavy metals and volatile organic compounds) through septic systems, dry wells, and cesspools.

Underground Storage Tank/Leaking Underground Storage Tank Programs

The Underground Storage Tank (UST) Program was established to address and prevent releases to soil and ground water from leaking USTs. An underground storage tank is defined as any tank system (including piping) that is at least 10 percent underground and stores a regulated substance. Over 1 million USTs in the United States contain regulated substances. The UST regulations require an owner or operator of an UST to: (1) implement release detection measures monthly in order to prevent releases; (2) find and report suspected releases to the implementing agency; and (3) take remedial actions to clean up contamination resulting from UST releases. Spills and leaks from USTs can contaminate both soils and ground water.

The Leaking Underground Storage Tank (LUST) Program was instituted to address leaking USTs that pose an imminent and substantial threat to human health and the environment. The LUST Trust Fund is a fund generated from revenues accumulated from taxes on shipment and purchase of petroleum products and is to be used when a leaking UST poses a threat to human health and the environment and (1) no responsible party can be found; (2) the source is unknown; (3) the responsible party is insolvent; or (4) the responsible party is recalcitrant. If the

site meets the LUST criteria, the implementing agency can perform site investigations and corrective actions to mitigate the threat to human health and the environment. If the responsible party is found and determined to be financially solvent, the implementing agency usually pursues cost recovery from the responsible party for the costs incurred at the site to reimburse the LUST Trust Fund.

Each of the three Groundwater Unit programs conduct data gathering and field investigation activities in support of decision making processes unique to each program. Each ground water investigation project will consist of environmental sampling of different media in order to obtain chemical, physical, and/or biological analyses to:

- determine baseline and background concentrations;
- confirm the presence or absence of pollutants or contaminants;
- determine the source of contamination;
- delineate the horizontal and vertical distribution of contaminants;
- evaluate rate and direction of contaminant transport;
- determine eventual fate of identified contaminants; and
- determine the effectiveness of treatment or remediation.

Because of the variability in the scope of work involved in the field investigations and project work of the Groundwater Program, this QAPP prescribes a general methodology for addressing the QA/QC elements more specifically in a SAP. Each ground water investigation data gathering effort will be addressed separately in the SAP, based on site-specific needs that will determine the scope and type of sampling, data collection procedures, and data quality objectives.

Project/Task Description

Ground water investigations, evaluations, and protection of underground sources of drinking water involve a variety of activities including program development, field investigations, multimedia sampling, and other types of data collection. All data collection activities must follow Standard Operating Procedures (SOPs) selected to address the scope of work and data quality objectives for the individual projects. Standard Operating Procedures for the types of field sampling, data collection, and other types of project work performed by the Groundwater Unit are listed in the bibliography in Appendix A. These documents will be available to all members of the Groundwater Unit.

Before any data collection event, a SAP will be developed to address the site-specific QA/QC elements as directed in this QAPP. SAPs will include discussions on:

- Site history and background information;
- Objective of the data collection effort;
- Rationale for the types of data to be collected, including the acceptable level of decision

- errors to be used as the basis for establishing the quantity and quality of data required;
- Measurements that will be made during the course of the field project and the conditions under which they will be made;
- Data precision, accuracy, representativeness, completeness, and comparability required;
- Applicable technical, regulatory, or program-specific quality standards, criteria, or objectives;
- Any special personnel and equipment requirements;
- Assessment tools needed (i.e., program technical review, peer reviews, surveillance, and technical audits) for the project;
- Schedule or time line for work to be performed; and
- Project and quality records required, including types of reports to be generated by the project activities, and how these records will be maintained and preserved.

Quality Objectives for Measurement Data

The data quality goals will vary according to the type of data collection project being conducted. In general, the data quality goals will be based upon the legal requirement for evidence in enforcement cases and the laws and implementing regulations mentioned previously. For each project, the SAP will address the following data quality objectives:

- Data needs and uses, including the type of data required and the use of that data in the program decision-making process;
- Parameters of interest, including the type of chemicals, contaminants, or other relevant parameters required for the project;
- Action levels or standards upon which decision will be made, and the affect of these levels and standards on laboratory analytical methods;
- Summary data quality indicator statistics discussed in Table 1 for each type of matrix to be sampled, where applicable; and
- Schedule for work to be performed, including the time period, time constraints, and location.

Sampling events conducted within the Groundwater Unit may involve collection of samples of opportunity, that were unplanned at the time the field project SAP was developed, but are necessary to determine the presence or extent of contamination unexpectedly encountered on the site. The development of formal data quality objectives will not be applicable for samples of opportunity. Sampling and analytical techniques that are consistent with SOPs will be used to ensure that representativeness and comparability are addressed to the maximum extent possible, given the constraints of the type of project being conducted for the collection and analysis of samples of opportunity. Precision, accuracy, and measurement range also will be addressed by employing standard operating procedures.

Table 1. Data Quality Indicators to be addressed in the Sampling and Analysis Plan.

Data Quality Indicators	Definition
Precision	The degree of agreement among repeated measurements of the same characteristic, or parameter, indicative of consistency in sampling methodology.
Accuracy	The measure of confidence that describes how close a measurement is to its "true" value.
Measurement Range	The range of reliable readings of an instrument or measuring device, as specified by the manufacturer.
Representativeness	The extent to which measurements taken actually represent the true environmental conditions.
Comparability	The degree to which data can be compared directly to similar studies. Data comparability is improved by using standardized sampling protocol, analytical methods, and units of reporting.
Completeness	The comparison between the amount of data planned to be collected as indicated in the SAP and the amount of usable data actually collected, expressed at a percentage.

Documentation and Records

When ground water samples are to be collected, the *Minimum Set of Data Elements for Ground Water Quality* will be addressed in the documentation of sampling and the transfer of analytical results into a database. These 21 elements are included in Table 2. Explanation of each element is included in *Definitions for the Minimum Set of Data Elements for Ground Water Quality*, EPA 813/B-92-002, July, 1992. These data elements are discussed further in the following section.

Detailed field notes will document sampling activities and any deviations from SOP. Field notes, inspection reports, photographs, and data from laboratory analyses will be maintained within the Groundwater Program Unit in Denver, CO.

Sampling Process Design

Specific sampling activities will be addressed in the SAP for each project, according to Standard Operating Procedures. The types of matrix to be sampled, target analytes, sampling

frequency, sampling period, and sampling equipment to be used will be variable among projects and will depend on the specific conditions present at each project site. Project scheduling time lines and time constraints, rationale for sampling plan, and sample site selection will be discussed in each SAP.

If hazardous materials and/or waste stream sampling is required, as determined by the project team, protocol selections will be based on site conditions, discussions with the team leader, lab analyst, and Regional staff as the situation requires. Usually only sampling requiring Level C protective equipment or less will be conducted during routine field investigations. Level C protective equipment includes:

- full-face air-purifying respirator,
- escape mask,
- chemical suit,
- steel-toed boots,
- disposable, chemical-resistant outer boots,
- hard hat, and
- chemical resistant inner and outer protective gloves.

If a greater level of protection is required, the need and specific arrangements for such sampling will be discussed and agreed upon between teams members and regional program and health and safety staff.

The sampling process design will also address the minimum set of data elements (MSDE) for groundwater quality, included in Table 2, which fulfills the requirements of EPA Order 7500.1A. This policy applies to all groundwater collection activities directly performed by EPA staff and its contractors, including those involved in enforcement activities. The purpose for the MSDE is to facilitate the management and sharing of data within the groundwater community, including States, local governments, the regulated community, EPA, and other Federal agencies. These 21 elements provide information to data users and decision makers that enable them to assess the quality and integrity of the groundwater data they are accessing.

Sampling Methods Requirements

The SAP for each project will specify the experimental design, data collection design, and sampling methods requirements according to Standard Operating Procedures including:

- sampling strategy,
- type and number of samples required,
- sampling locations and frequencies,
- matrices to be sampled,

- parameters to be analyzed,
- how samples will be collected,
- equipment and containers to be used, and
- holding times.

The sampling methods, preservation, and holding times will be determined according to Table II in 40 CFR Part 136.3 or according to the selected analytical methods as defined in the DQOs, and in consultation with QA and laboratory staff as needed, so as to assure that the data obtained achieve the data quality goals specified. For ease of reference in the field by field team members, it is helpful to present this information in tabular form in the SAP.

Table 2. Minimum Set of Data Elements for Ground Water Quality

Minimum Set of Data Elements for Ground Water Quality	
1. Data Sources	11. Well identifier
2. Latitude	12. Well use
3. Longitude	13. Type of log
4. Method used to determine latitude and longitude	14. Depth of well at completion
5. Description of Entity	15. Screened/open interval
6. Accuracy of latitude and longitude measurements	16. Sample identifier
7. Altitude	17. Depth to water
8. Method used to determine altitude	18. Constituent or parameter measured
9. State Federal Information Processing Standard (FIPS) Code	19. Concentration/value
10. County FIPS Code	20. Analytical results qualifier
	21. Quality assurance indicators

If unexpected events or conditions in the field cause deviation from protocol in the SAP or SOPs, then the field team leader will decide on an alternative course of action, and any procedures that are modified will be fully documented in the field notes.

Decontamination of reusable sampling equipment will be conducted according to the procedures included in the quintessential SOP, *Minimum Requirements for Field Sampling*

Activities, referenced in Appendix A.

Sample Handling and Custody Requirements

Samples collected in the field will be properly labeled with a sample identification label that includes information such as sample location description, sample number, time and date of collection, sample type, samplers' names and signatures, and type of preservative used. The field team will follow appropriate chain-of-custody procedures during sampling handling from the time the sample was collected until the sample arrives at the laboratory. The field team must also ensure that once the laboratory takes possession of the samples, there are procedures in place to document that the samples received and the analytical results reported for each sample are verifiable.

These guidelines will be used for sample handling:

1. *Field custody procedures:*

Samples will be collected by EPA personnel, or in the presence of EPA personnel, and placed into clean sample containers of the appropriate type. An EPA Region VIII sample tag containing pertinent information will be attached to each sample container. The field team leader is responsible for the care and custody of the samples collected until they are transferred or dispatched properly. It is the responsibility of the field team leader to ensure that proper custody procedures are followed during the field work.

2. *Transfer of custody and shipment:*

a. Sample information must be recorded on a Region VIII Chain-of-Custody Record, which contains sample identification and analyses to be performed. The Chain-of-Custody form must accompany the samples when they are transferred into the possession of another individual. Both the individuals relinquishing and receiving will sign, date, and note the time of transfer on the Record. The Record verifies sample custody transfer from the sampler, often through another person, to the analyst in a laboratory.

b. To ensure sample security, samples must be packaged properly for shipment (e.g., in a large bag sealed with the EPA Official Sample Seal placed in a sealed ice chest with ice if necessary) and dispatched to the laboratory for analysis. A separate Chain-of-Custody Record must be included within each ice chest. The method of shipment, courier name(s), and other pertinent information are entered into the "Remarks" section of the Record.

c. Whenever samples are split with another party, it is to be noted in the "Remarks" section of the Chain-of-Custody Record. The note indicates with whom the samples are being split, and is signed by both the sampler and the recipient. If the split is refused, this will be noted and signed by both parties. The person relinquishing the samples to another party should request the

signature of a representative of the other party, acknowledging receipt of the samples. If a representative is unavailable or refuses to sign, this fact is noted in the "Remarks" section. When appropriate (e.g., where the representative is unavailable), the Record should contain a statement that the samples were delivered to the designated location at the designated time.

d. All sample shipments must be accompanied by the Region VIII Chain-of-Custody Record identifying its contents. The original Record will accompany the shipment, and a copy will be retained by the project officer/team leader.

e. If sent by mail, the package must be registered with return receipt requested. If sent by common carrier, the carrier's name and other pertinent information are entered on the Chain-of-Custody Record in the transfer of custody fields (e.g. *in transit via Fed Ex.*). Shipment receipts must be attached to the Record as part of the permanent documentation.

Prior to shipping any samples, the field manager must classify the samples collected as either *environmental* or *hazardous materials samples*. Guidance for complying with US Department of Transportation (DOT) regulations in shipping is covered in 49 CFR Parts 171-177. Depending on the amount of preservative added to a sample, some samples may meet the conditions for hazardous materials and must be shipped in accordance with procedures described in the current US DOT Regulations (see Table 6 in the *Minimum Requirements for Field Sampling Activities* for types of samples and preservatives that may require special consideration).

f. A record custodian or clerk should receive and date all samples as they arrive and place them in a locked and secured area.

Analytical Methods Requirements

The analytical methods required for different types of environmental samples are dependent both on the specific result sought for the sampling event and on the compatibility of the analysis method with the sample and matrix. It is important to check with the laboratory prior to the sampling event to confirm that the analytical methods requested are compatible for the sample matrix. Types of matrices that might be sampled for Groundwater Program Unit projects include water, air, soil, sludge, and sediment. Analysis methods must be chosen to meet the appropriate data quality objectives. Methods for non-routine analyses must be specified in the site-specific sampling and analysis plan.

Analyses of any samples collected will be performed either by contract laboratories or the Region VIII lab in Denver, CO. The QA/QC plan for Energy Labs, the laboratory that has been contracted to perform sample analyses for the UIC program, is referenced in Appendix A and is available in the Groundwater Unit. The QA/QC plan for the Region VIII laboratory is available upon request from the lab.

For laboratory analyses that are not arranged through the Region VIII sample broker, but are handled through a contract laboratory, the following information should be forwarded to the Region VIII sample broker:

- list of facilities where samples were collected
- field team leader
- Sampling and Analysis Plan signature page
- sampling date
- sample matrices and number of samples
- laboratory name and address
- analytes measured
- cost of analyses

Quality Control Requirements

The quality control requirements for each field project will be addressed specifically in the SAPs developed for each sampling effort. The types of quality control samples that may be required and the purpose for each type are listed in Table 3.

Instrument Calibration and Frequency

All field analytical instrument calibration procedures and scheduled maintenance will be conducted in accordance with the manufacturer's recommendations. Examples of typical field instrumentation that may be used in Groundwater Unit field work, and the calibration requirements for each, are included in Table 4.

Assessment and Response Actions

Assessment

Review of the Groundwater Program sampling activities is the responsibility of the project or field team leader, in conjunction with the Groundwater Unit Supervisor and the Regional Quality Assurance officer. After the sampling event, the team will meet to discuss problems encountered and methods to correct the problems.

Any Groundwater Program field and laboratory activities may be reviewed by the Region VIII Quality Assurance group at its discretion. Systems and data quality audits may be performed at any time. Any special assessments unique to a site will be addressed in the SAP for that sampling effort. Any identified procedural problems will be documented and corrected based on recommendations from the QA reviewer.

Table 3. Guidelines for types of quality control samples.

Type of QC sample	Purpose
duplicate sample (True duplicates can be collected only from homogeneous systems such as open flowing water. All other samples, even well samples, are co-located samples.)	Two samples collected in different containers at the same time and location used to evaluate natural variability in the system being sampled and precision of field sampling techniques.
co-located sample	Samples collected in different containers at the same time and location used to evaluate natural variability in the system being sampled.
container blank (Performed by lab if the lab provides the containers.)	Used to evaluate the contamination of the sample matrix with the analytes of interest contributed by the container into which the sample is placed.
preservative blank (Performed by lab if the lab provides the preservatives.)	Used to evaluate the contamination of the sample matrix with the analytes of interest contributed by the sample preservatives.
trip blank (for VOCs only)	Used to test for any VOC contamination resulting in the handling of VOC samples.
field blank	Used to detect introduction of contamination into sample throughout every step of the process including sample collection, transport, and lab analysis.
Equipment or rinseate blank	Used to check for cross contamination from sample to sample caused by the reuse of field equipment and to evaluate field decontamination procedures.
Spiked sample or Performance Evaluation (PE) samples	Used to measure accuracy of the analytical technique.
Background samples	Used to provide baseline data on the natural presence of analytes of interest in the sample matrix outside the area where contamination is known to occur.

Table 4. Summary of Guidelines for Calibration and QC Procedures for Field Analyses

Applicable Parameter	QC Check	Suggested Minimum Frequency	Suggested Acceptance Criteria	Suggested Corrective Action
Moisture	Duplicate sample	1 per 20 samples	% solid RPD \leq 5%	Correct problem, repair measurement. If still out, flag data
pH(soil)	2 point calibration with pH buffers	1 per 10 samples analyzed	\pm 0.05 pH unit	Check with new buffers; if still out, repair meter; repeat calibration check.
	pH 7 buffer	At each sample location	\pm 0.1 pH unit	Recalibrate.
	Duplicate sample	10% of field samples	\pm 0.1 pH unit	Correct problem, repeat measurement. If still out, repeat calibration.
Conductance	Calibration with KCl standard	Once per day at beginning of testing	\pm 5%	If calibration is not achieved, check meter, standards, and probe; recalibrate
	Field duplicate	10% of field samples	\pm 5%	Correct problem, repair measurement.
pH (water)	2-point calibration with pH buffers	Once per day	\pm 0.05 pH units for every buffer.	If calibration is not achieved, check meter, buffer solutions, and probe; replace if necessary; repeat calibration.
	pH 7 buffer	At each sample location	\pm 0.1 pH units	Correct problem, recalibrate
	Field duplicate	10% of field samples	\pm 0.1 pH units	Correct problem, repeat measurement
Temperature	Field duplicate	10% of field samples	\pm 1.0°C	Correct problem, repeat measurement

Table 4. Continued

Applicable Parameter	QC Check	Suggested Minimum Frequency	Suggested Acceptance Criteria	Suggested Corrective Action
Turbidity	Calibration with one formazin standard per instrument range used	One per day at beginning of testing	± 5 , units 0-100 range; ± 0.5 , units 0-0.2 range; ± 0.2 , units 0-1 range	If calibration is not achieved, check meter; replace if necessary; recalibration
	Field duplicate	Once per day at 10% of field samples	$RPD \leq 20\%$	Correct problem, repeat measurement
Organic vapor concentrations (FID and PID)	3 point calibration	Monthly	correlation coefficient ≥ 0.995	Recalibrate; check instrument and replace if necessary
	Calibration verification and check	Daily at beginning and end of day	Response $\pm 20\%$ of expected value	Correct problem, Recalibrate.
Oxidation-reduction potential (Eh)	Sensitivity verification	Daily	ORP should decrease when pH is increased	If ORP increases, correct the polarity of electrodes. If ORP still does not decrease, clean electrodes and repeat procedure.
	Calibration with one standard	Once per day	Two successive readings ± 10 millivolts	Correct problem, Recalibrate.
	Field duplicate	10% of field samples	± 10 millivolts	Correct problem, repeat measurement.

¹ the Practical Quantification Limit is 5 to 10 times the method detection limit

² Relative Percent Difference (RPD):

$$RPD = \frac{|X_1 - X_2| \times 100}{X_1 + X_2 \div 2}$$

where X1 and X2 are the analytical values for each of the duplicate samples.

Response

Any problems encountered during the assessment activities will be reviewed by the program teams to identify and evaluate methods for improvement, and appropriate corrective action will be taken and documented.

Data Review, Validation, and Verification Requirements

Once the analytical data is received from the laboratory, field and laboratory data should be reviewed by the Project Manager, field team leader, and/or Regional QA Officer to evaluate whether or not data quality meets the project needs as described in the data quality objectives. The data verification process involves an evaluation of the extent to which conclusions can be correctly and reliably drawn from the data. The criteria used to review, validate, and verify the data should be addressed in the SAP. The end goal of the data quality validation process quality is a decision to either accept the data unconditionally, reject them, or accept them with qualifications. The steps subject to review in the validation process should include:

- the design of the sampling process;
- the procedures used for sample collection and handling;
- analytical methods and procedures;
- lab and field QC procedures and results;
- calibration for field and lab equipment, and
- any data reduction and processing that may have been involved.

If, during the review, it is determined that there has been any deviation in any of the above steps from the procedures designated in the referenced SOPs, project SAP, or this QAPP, then each deviation must be evaluated for the potential effect it may have had on the usability and quality of the resulting data. Any deviations from designated procedures must also be reviewed for impact on the decision-making processes that are based on the impacted data.

Validation and Verification Methods

The data validation and verification methods should be described in the project SAP, including the roles and responsibilities for each step in the process. Possible steps involved in the process include (but are not limited to):

- checking the sample identification numbers against the field notes and chain of custody forms to ensure that all the cross-references are correct;
- comparison of computer entries to data sheets and field notes;
- identification of data gaps;
- analyzing QC data such as chain-of-custody information, spikes, equipment calibration;
- checking calculations;

- examining raw data for outliers; and
- reviewing graphs and tables.

Appendix B includes a check list of steps to evaluate in the data validation and verification process.

Reconciliation with Data Quality Objectives

The project SAP must specify the methods for evaluating whether or not the data are the correct type, quantity, and quality to fulfill the requirements of the project. Projects for which formal Data Quality Objectives have been developed may require a formal Data Quality Assessment. This process, addressed in the *EPA Guidance for Data Quality Assessment*, (EPA QA/G-9), involves the use of graphical and statistical tools that are used to evaluate data for fitness in decision making.

For projects with less complex Data Quality Objectives, it may suffice to address this step by performing calculations and determinations for precision, completeness, and accuracy and implementing corrective action as needed. If the data quality indicators do not meet the project specifications as described in the project Data Quality Objectives, data may be qualified and the acceptance conditions documented, or the data may have to be discarded and resampling performed. The cause of failure should be evaluated. If the cause is found to be equipment failure, calibration/maintenance techniques should be reassessed and improved. If the problem is found to be sampling team error, team members should be retrained. Any limitations or conditions on data use should be fully documented to allow decision makers to evaluate the extent to which decisions can be supported by the data in question.

If failure to meet project specifications is found to be unrelated to equipment, methods, or sample error, then the specifications may need to be revisited to evaluate whether or not they are practical for the project needs and budgetary constraints.

Appendix A

Bibliography of Standard Operating Procedures Employed by Programs Within the Groundwater Unit.

Standard Operating Procedures for the Region VIII Underground Injection Control Program, USEPA, Region VIII, UIC Program, October, 1997.

Minimum Requirements for Field Sampling Activities, USEPA, Region VIII, Technical and Management Services, September, 1996.

Compendium of ERT Waste Sampling Procedures, USEPA, Office of Solid Waste and Emergency Response, EPA/540/P-91/008, January, 1991.

Compendium of ERT Groundwater Sampling Procedures, USEPA, Office of Solid Waste and Emergency Response Directive 9360.1-06, January, 1991.

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EPA Region 8 Underground Storage Tank Program Inspection and Field Citation Manual, Final Guidance: UST-E-001-92, 3rd Revision, Oct. 1997.

RBCA Guidance for Petroleum Releases at Underground Storage Tank Sites in Indian Country, Final Draft Guidance: Sandy Stavnes, EPA Region 8, and Richard Mattick, EPA/OUST, Sept. 1997.

How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites, OSWER, EPA510-R-96-001, Sept, 1996.

Expedited Site Assessment Tools for Underground Storage Tank Sites; A guide for regulators, OSWER, EPA510-B-97-001, March 1997.

How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A guide for corrective action plan reviewers, OSWER, EPA510-B-95-007, May 1995.

Appendix B

Suggested steps to review in the data validation and verification process, from *EPA Guidance for Quality Assurance Project Plans, (EPA QA/G-5)*

Initial Calibration and Frequency

- initial calibration
- continuing calibration
- calibration standards used as compared to analytes of interest and concentrations

Standards Required vs. Standards Used, and Frequency

- internal standards (standard used, acceptance criteria met?)
- standard levels and concentrations
- analytes (target, concentration, acceptance limits)
- laboratory control

Qualitative or Quantitative Tests Performed

- method blanks
- matrix blanks
- frequency
- QA/QC criteria for acceptance

Samples analyzed, type (organic, inorganic, etc.)

- sample blanks
- matrix spikes
- matrix spike duplicates

Types of Instruments Checked

- criteria used for accepting instrument performance (QA/QC, response factors, precision, and accuracy, etc.
- For software and hardware, criteria should be established to demonstrate suitability to meet the tests and challenges for the tasks expected for the system.

Actual Sample Analysis

- sampling and analysis plan (sampling design, sample analysis, sampling execution)
- holding times
- volume or weight required vs used
- internal standards and blanks (requirements met?)
- surrogate spike recoveries (system monitoring compounds for VOCs)(present, required QA/QC met? Acceptable limits, recoveries met?)
- analytes of interest (how analyzed, identified, quantification and/or qualified, criteria used)
- analytes of non-interest (how analyzed, identified, quantification and/or qualified, criteria used)
- duplicates
- method precision and accuracy
- ICP serial dilution (for metal concentrations >10 MDL or off standard calibration curve)
- target compound identification (for organic compounds)
- tentatively identified compounds (for organic compounds)
- ICP interference check samples (for metals)

Budget assessments and costs assessments

- projected costs vs. actual costs
- cost overruns justified?

U.S. EPA REGION VIII
MINIMUM REQUIREMENTS
FOR
FIELD SAMPLING ACTIVITIES



September 1996

This replaces the document "U.S. EPA Region VIII Standard Operating Procedures for Field Sampling Activities, Version 2" dated June 1994.

U.S. Environmental Protection Agency
Technical and Management Services
Denver, Colorado

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**U.S. EPA REGION VIII
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**U.S. Environmental Protection Agency
Region VIII**

Denver, Colorado

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U.S. EPA REGION VIII
MINIMUM REQUIREMENTS
FOR
FIELD SAMPLING ACTIVITIES

SECTION 1.0 GENERAL PROCEDURES FOR FIELD SAMPLING ACTIVITIES

1.1 INTRODUCTION

This document was prepared to assist all U.S. Environmental Protection Agency (EPA) Region VIII personnel, state personnel, and contractor/subcontractor personnel who conduct field activities for or on behalf of EPA Region VIII. This document presents minimum requirements for field sampling activities.

An important purpose of this document is to serve as a guide in the planning and implementation of field sampling programs. The minimum requirements described in the document are intended to ensure consistency in data collection activities in order to produce comparable quality data on a Region-wide basis. The sampling sections outline the minimum requirements and general guidelines for completing the specified activities. The minimum requirements allow for flexibility (as appropriate) to accommodate program or project-specific goals and other governing requirements (e.g., regulatory mandates).

1.1.1 Use of this Document

The minimum requirements specified in this document apply to field activities carried out by or on behalf of EPA Region VIII unless they are superseded by other requirements such as those contained in applicable regulations, contracts, existing enforcement documents (e.g., Consent Decrees), and other existing governing/binding documents. Note that the scope of applicability of

some of the Regional requirements presented in this document may be further defined in the section(s) in which the requirement(s) are explained.

The personnel and organizations to whom the requirements apply must consult this document when developing new plans and standard operating procedures (SOPs) that include activities addressed in this document. Existing SOPs also must be reviewed for consistency with the corresponding requirements in this document before being implemented for new activities. Deviations must be handled as described below.

Deviations from the minimum requirements specified in this document must be documented. The documentation must address the reason for the deviation and the potential impact, if any, on Regional data comparability, and on use of the data for its intended purpose. Deviations which are identified during the planning stage must be documented in the appropriate planning document(s) (e.g., Quality Assurance Project Plan (QAPP) and/or Sampling and Analysis Plan (SAP) or in amendments to the plan(s). (It is important that the data users are aware of any deviations which would affect their use/interpretation of the affected results). Deviations identified in the field (e.g., "field changes") must be addressed to the laboratory, if numbers of samples or analyses change. These changes will be identified in an addendum sent to the project officer and Regional Quality Assurance Officer within one week of the change and documented in the results report for the affected data. Deviations identified in the field also need to be recorded in the appropriate field document(s) (e.g., bound logbook), although it might not be feasible for the field documentation to include a discussion on the potential data impact. Questions regarding the applicability of the requirements or the handling of deviations should be addressed to the Regional Quality Assurance Officer.

Ideally, the likely field conditions and corresponding procedural modifications (e.g., "Plan Bs") will be anticipated in the Quality Assurance (QA) planning document and approved in advance along with the plan. For example, the SAP could describe how alternative sampling locations will be

selected if the anticipated sampling location is found to be unsuitable in the field. The potential for changes in data needs, such as additional samples, could also be addressed in advance in the plan.

1.1.2 Standard Operating Procedures

The main objective for this document is to communicate in one convenient compilation the Region's minimum requirements and recommendations for procedures related to field sampling activities. It is anticipated that most users of this document will consult it for clarification of Regional requirements and recommendations for field-related work. It is not expected that most users will either need or want to use the procedures in the this document as their own SOPs. In fact, the presentation of most of the information in this document is not appropriate to use "as is" for step-by-step procedures to guide field personnel. Most users are expected to consult this document to ensure that their own SOPs are compliant with the Regional requirements, and use any recommendations as guidance.

The compilation of Regional requirements and recommendations in this document may be incorporated by reference in work assignments and Statements of Work (SOWs) for enforcement agreements, such as Consent Decrees, etc.

This document replaces the June 1994 field guidance entitled, "U.S. EPA Region VIII Standard Operating Procedures for Field Sampling Activities, Version 2." This document incorporates portions of the documents that were referred to as SOPs (e.g., "SOP #4.1 for Well Purging") in the June 1994 field guidance. The full text of many of these "SOP" documents, referenced in Section 1.8, is still available separately. These separate "SOP" documents are referenced in the sections of this document which correspond to the subject matter of each "SOP". Therefore, the "SOPs" have been retained as supporting documents which contain more detailed information on the procedures. It is anticipated that project managers will consult the excerpts in the main document, and that the personnel responsible for writing plans and/or carrying out the procedures will also consult the relevant supporting "SOP" documents. These documents are available from either Technical and

Management Services Laboratory program (Biology) or the Programs Support program in Environmental Protection and Remediation.

In this revised document, the use of the term "SOP" refers to documents containing step-by-step cookbook-type procedural descriptions. The existing documents previously referred to as "SOPs," such as "SOP #4.1 for Well Purging", are not generally presented as stepwise procedures.

It would be impractical to issue step-by-step procedures or procedures that would cover every potential field application, especially those that may have a potentially wide variety of applications, such as groundwater well sampling. The sections in this document describe the appropriate order of activities when order is important. The QA Program does present the procedures in a step-by-step format for routine procedures that are relatively simple and have a more manageable range of applications, such as sample packaging.

The existence of this document and any directive regarding its use will not preclude individual programs (e.g., Superfund) or technical groups (e.g., Regional groundwater forum) from developing and issuing their own SOPs, standards, etc. for field procedures. It is required that these separate SOPs, etc. be compliant (within the allowed flexibility described in this document and/or related directive) with any corresponding requirements in this document.

1.1.3 Document Revision and Distribution

This document or selected sections will be revised periodically, to incorporate improvements in technology, reflect changes in policy, and add requirements and/or guidelines for additional field activities. Whenever this occurs, revisions will be sent to those individuals identified on a mailing list prepared and maintained by the Region VIII Quality Assurance Program. The use of document control headers in this document will allow for revision and replacement of individual sections, without requiring regeneration of the entire document. For example, when new SOPs or other pertinent documents are developed or revised in the Region, these documents may be listed in a

revised reference section for this document, and this revised section alone could be distributed to document users. Users of this document are encouraged to maintain it in a 3-ring binder or similar arrangement to facilitate the incorporation of revisions.

To obtain a copy of this document and/or be added to the mailing list for updates, call the EPA Region VIII office in Denver at (303) 312-6312 and ask to be connected to the Quality Assurance Program. This document also may be made available on diskette or via electronic file transfer in Wordperfect 5.1, 6.0, 6.1 or ASCII format. (The requestor may need to supply an appropriate diskette). Please contact the QA Program to ask about the availability of the document in these formats.

1.2 PREPARATION FOR FIELD ACTIVITIES

1.2.1 General Requirements for Designing a Field Investigation

The same care must be exercised in planning the design and implementation of field investigations and sampling programs that is exercised in the analysis of samples in the laboratory. No analytical result is better than the sample from which it was obtained.

When designing a field investigation or a monitoring program, the study objectives must first be defined with respect to the desired use of the data to be generated and the corresponding quality of data that is needed. A systematic planning process called the Data Quality Objectives (DQOs) process was developed by EPA to ensure that the type, quantity, and quality of environmental data generated are appropriate for their intended use. The DQOs identified through the planning process are qualitative and quantitative statements intended to accomplish the following:

- Clarify the study objective(s);
- Define the most appropriate type(s) of data to collect;
- Determine the most appropriate conditions under which to collect the data
- Define the precision, accuracy, completeness, representativeness and comparability of the data required for the project; and
- Specify the acceptable level of decision errors that will be used as the basis for establishing the quantity and quality of data needed.

The procedures for developing DQOs are described in EPA QA/G-4 "Guidance for the Data Quality Objectives Process, Final Guidance." DQOs should be evaluated and modified as needed after each stage or phase of an investigation.

Every field investigation which generates environmental data must be conducted in accordance with an approved Quality Assurance Project Plan (QAPP) to ensure that DQOs will be met. Policy established by EPA Order 5360.1 requires participation by all EPA programs in a centrally-managed quality assurance program to ensure that environmental data produced is of known quality. Each program has the responsibility to identify in a QAPP the minimum procedures required to assure that goals for precision, accuracy, completeness, representativeness, and comparability of data generated are satisfied. In Region VIII, QAPPs may be either generalized to address an entire program, or may be project/site-specific. Exhibit B (following the Section 1.0 tables) shows the 16 topics ("elements") required to be addressed in Region VIII QAPPs. A detailed discussion of the required QAPP elements and development of DQOs is presented in a document entitled "EPA Requirements for Quality Assurance Project Plans for Environmental Data Operations" (EPA QA/R-5) August 1995 (25). The Region VIII QA Program has also developed work sheets based on the EPA QA/R-5 document which can be consulted when preparing or reviewing QAPPs. *Please note that while most recent QAPPs prepared for Region VIII are written to meet the required 16 QA/R-5 elements, some QAPPs must meet other superseding or additional requirements. For example, some remaining contract work assignments require QAPPs to follow the older guidance, "EPA-600/4-83-004 Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans (005/80)." Consult the applicable requirements (e.g., regulations, enforcement agreement, contract, Regional Quality Management Plan, etc.) to determine what QA planning specifications must be met.*

Region VIII allows the required EPA QA/R-5 QAPP elements to be addressed for a field investigation using a combination of a QAPP and a sampling and analysis plan (SAP). A SAP is typically based on a parent QAPP and used to provide details of particular field investigations, such as sample numbers and locations. In Region VIII, there is no requirement for a separate SAP if the required QAPP elements provide the specifics for the field investigation. An example outline for a SAP is provided as Exhibit A, following the Section 1.0 tables. *Note that the terms for QA planning documents, such as SAPs, may be used somewhat differently by individual programs. For example, the term field sampling plan (FSP) is used in Superfund to refer to a SAP as it is described in this paragraph.*

Project managers must be familiar with the applicable QA requirements when planning field work. Field personnel must be familiar with the governing QA plans (e.g., QAPP, project-specific SAP, any applicable SOPs), before performing the corresponding field work. The QAPP and any applicable SAP must be prepared and approved in writing before the sampling activities begin. Consult the Regional Quality Management Plan (27) for any exceptions to this requirement. Both QAPPs and any applicable SAPs must be approved by the responsible official, such as a project manager, who is designated by the program/functional area to have approval authority. The Regional Quality Assurance Management Plan should discuss the approval authorities for each program/functional area or administrative situation (e.g., State-lead effort funded by EPA). *Note that the term "program" refers to the current Region VIII organization (Oct. 1, 1995) and does not necessarily refer to specific programs such as water, air, hazardous waste, etc.* If the approval authority is not clear, contact the Regional Quality Assurance Officer for assistance. The Regional Quality Assurance Office can also provide technical review assistance as requested, but each program/functional area is responsible for approval. An exception to this is in the case of QAPPs for certain assistance grants involving environmental data collection where QAPP approval by the Regional Quality Assurance Officer is required.

If significant changes to the approved plans are required due to changes in field conditions or data needs, the changes must be approved by the Project Manager. Copies of the changes and documented approval must be included as attachments (e.g., amendments) to the QAPP and any other affected documents, such as the SAP, Work Plan, and most important, the results report. Changes that are made in the field must also be documented in field records.

1.2.2 Media Sampled and Activities Conducted

Several media can be sampled in the process of conducting a sampling program, and the samples collected can be analyzed for biological, chemical and physical characteristics. The media sampled may include source or waste material, ground water, surface water, soil, sediment, air, and biological

specimens. Examples of sample types or media, and examples of the measurements that can be collected from each medium are as follows:

■ **Source and Waste Sampling**

Sample type or medium sampled

- Drums and tanks
- Impoundments, lagoons, and seeps
- Solid waste
- Highly contaminated environmental media near sources
- Waste streams

Measurements

- Flow rate
- Physical characteristics (fluid, solid, density, viscosity, etc)
- Chemical characteristics and Contaminants present

■ **Ground Water Sampling**

Sample type or medium sampled

- Monitoring wells
- Industrial Production wells
- Municipal and Public Supply Wells
- Domestic supply wells
- Livestock supply wells
- Springs and seeps
- Test borings or test pits

Measurements

- Field parameters (turbidity, pH, conductivity, temperature, etc.)
- Water levels
- Discharge or recovery rates
- Aquifer characteristics (from pumping tests)
- Water chemistry
- DNAPLs and LNAPLs present: chemical & physical parameters
- Contaminants present

■ **Surface Water Sampling**

Sample type or medium sampled

- Ponds and lakes
- Streams and rivers
- Surface Runoff

Measurements

- Field parameters (e.g. pH, conductivity, temperature, etc.)
- Flow rates
- Water chemistry
- Biologic parameters
- Depth and bottom configuration

■ **Soil Sampling**

Sample type or medium sampled

- Surface soil
- Subsurface cuttings
- Subsurface core
- Rock core

Measurements

- Depth of collection
- Chemical and contaminant characteristics
- Physical characteristics (moisture, density, etc.)
- Physical appearance (color, particle size, etc.)
- Laboratory permeability and/or porosity
- Organic content
- Geophysical properties with borehole logging
- Headspace and other field monitoring for volatiles

■ **Sediment Sampling**

Sample type or medium sampled

- Stream and lake bottom grab samples
- Stream and lake bottom cores

Measurements

- Depth below water and below surface
- Chemical and contaminant characteristics
- organic content

- Physical characteristics and appearance (color, particle size, density, etc.)

■ **Ambient Air Sampling**

Sample type or medium sampled

- National Air Monitoring Sites (NAMS)
- State and Local Air Monitoring Sites (SLAMS)
- Special Purpose Monitoring Sites (SPMS)
- Stationary source locations

Measurements

- sulfur dioxide
- nitrogen dioxide
- carbon monoxide
- ozone
- lead
- particulates

■ **Biological Sampling**

Sample type or medium sampled

- Terrestrial and aquatic flora
- Terrestrial and aquatic fauna

Measurements

- chemical composition
- contaminant concentrations
- species and age

The SOPs referenced in Section 1.8 describe procedures for sample collection activities for those media listed above (excluding unknown wastes). Waste sampling procedures cannot be generalized because the chemical characteristics and potential hazards of exposure to the concentrated material vary significantly, depending on the type of waste.

Each SOP outlines the basic components and requirements for completing a specific field activity, and indicates the level of detail required for project-specific SOPs and SAPs.

1.3 GENERAL SAMPLING PROCEDURES

1.3.1 Purposes for Sampling

Environmental media samples for chemical analyses are most commonly collected and analyzed to confirm the presence or absence of pollutants or contaminants, determine levels of concentration, delineate the horizontal and vertical distribution, evaluate rate and direction of transport, and determine eventual fate of the identified pollutants. Sampling activities may be conducted for site characterization, for ongoing monitoring programs, for compliance with permit conditions or during remediation and removal activities.

Appropriate sample collection requires consideration of many factors including the following:

- minimum sample volumes;
- selection of sample containers;
- sample preservation and holding times for matrix and requested analyses;
- general sample handling and subsampling;
- special handling of samples to be analyzed for volatile constituents;
- special handling of samples to be analyzed for low-concentration (trace) constituents; and
- quality control (QC) requirements.

These considerations are discussed in Sections 1.1 through 1.6 of this document.

1.3.2 Types of Samples

Different types of samples can be collected, depending on the needs of the data users and the eventual use of the data. One of the most important considerations in selecting the appropriate type of sample to collect is determining what the sample should represent: *Note that some regulations and*

corresponding requirements (e.g., permits) specify the type of sample (e.g., 24-hour composite) that needs to be collected.

Three basic sample types are listed below, followed by a discussion of the appropriate use of each type. Samples collected for QC purposes are discussed in Section 1.3.8.

- Grab or discrete samples (surface water, ground water, wastewater, waste, contaminated surfaces, soil, sediment sampling, etc.)
- Composite samples (surface water, wastewater, soil, sediment sampling, etc.)
- Continuous samples (usually collected with automatic collection devices, air samplers, etc.)

Grab Samples

A grab or discrete sample is an instantaneous collection of a portion of a single medium from a single location. Grab samples are typically used to characterize a medium at a particular location and time. The analytical results from grab samples can be used to characterize the level and distribution of contamination at a site, and to identify zones of increased or decreased concentration.

Composite Samples

A composite sample is prepared by combining or "compositing" several discrete samples of a single medium collected from different locations or at different times. Because they consist of combined samples, composite samples represent a physical average over a covered area or time. Composite samples may provide for representation of a wider area or time interval with fewer samples, but compositing may also obscure (by dilution) individual "hot spots" or concentration spikes. There are two basic types of composite samples, the simple composite, and the proportioned composite.

A simple composite is the total volume of sample prepared by combining fixed amounts of sample collected from several locations or at several time intervals from a single location. The three types of simple composites are as described below:

- Time Composite (TC): A sample comprised of a varying number of discrete samples collected at equal time intervals from the same location during the compositing period. The TC sample is typically used to sample flowing wastewater or streams. This procedure is appropriate only if flow rate is relatively constant.
- Areal Composite (AC): A sample composited from individual grab samples collected on an areal or cross-sectional basis. Areal composites are made up of equal volumes of grab samples. Each grab sample is collected in an identical manner. Examples of areal composites include sediment grab samples composited from quarter-point sampling of streams, and soil grab samples collected from grid points and composited.
- Vertical Composite (VC): A sample composited from individual grab samples collected from a vertical cross section. Vertical composites are made up of equal volumes of grab samples. Each grab sample is collected in an identical manner. Examples include composited grab samples collected from vertical profiles of soil/sediment columns, or vertical profiles of surface water bodies.

The proportioned composite sample applies mainly to flowing water or wastewater sampling and can be further divided into two basic types, 1) where the amount of sample collected is varied with flow, or 2) where the frequency of collection is varied with flow. A Flow Proportioned Composite (FPC) is a sample collected proportional to the flow rate during the compositing period by either a time-varying constant volume (TVCV) or time-constant varying volume (TCVV) method. The TVCV method is typically used with automatic samplers that are paced by a flow meter. The TCVV method is a manual method that individually proportions a series of discretely collected samples. The FPC is typically used when sampling wastewater.

Depth-Integrated, Flow-Weighted Stream Sampling

In situations where chemical homogeneity of a stream cross-section is uncertain, EPA Region VIII recommends the collection of Depth-Integrated, Flow-Weighted samples (DIFW). The collection method is similar to the equal width increment (EWI) method published by the U.S. Geological Survey. A summary of the DIFW method is provided in the following paragraphs:

After the total cross-sectional flow for a sampling station is estimated, the vertical flow point demonstrating the highest discharge rate is selected as the sample calibration point. At the calibration point a standard suspended sediment sampling device, fitted with a 1000 ml polypropylene sample container, is used to collect a depth-integrated sample from the water column. The suspended sediment sampler is lowered from the surface of the water to the stream bed, without disturbing the stream bed, and back to the surface at a constant transit rate. The rate used must not allow the sample container to overfill, because the calibration point is the point of maximum discharge.

The sample is then poured into a graduated cylinder and the volume is measured. The transit time and volume are recorded. Several attempts are generally required to estimate the appropriate transit time required to obtain the optimal sample volume. Once the optimal transit time has been established, the process is repeated two more times and the average volume (from three collections) at the fixed transit time is calculated for the calibration point. The fixed transit time for the calibration point becomes the fixed transit time for collecting a depth-integrated sample from each location along the section.

The sample volume to be collected from each location along the stream cross-section is estimated from its calculated discharge rate; each location's volume must be proportional to the calibration point. Each location's sample collected with the sediment sampler is measured into a graduated cylinder and the actual volume collected is recorded; volume in excess of the calculated volume is discarded into the stream. The discharge-proportioned volume is then poured into a 10-liter high-density polypropylene container, which is used to mix the composite sample and prepare the splits.

No decontamination is conducted between locations along a cross-section. However, all sampling equipment is rinsed with hydrochloric acid and deionized water between sampling station cross sections. Prior to collecting samples at each new station, the equipment is also rinsed three times with native water to further ensure no contaminant carryover. Equipment blanks shall be taken to ensure that the equipment decontamination procedure is adequate.

Continuous Samples

Continuous samples consist of a series of discrete samples collected from a medium at set time intervals, over a period of time. They are collected and analyzed to allow evaluation of changes in contaminant concentrations due to environmental, climatic or site influences, such as periods of facility operation. Continuous air samples are commonly collected to assess the impact of facility operations or the ambient air quality of a populated area over a specified period of time. Continuous surface water samples may be collected near an outfall to assess both the impact of discharges on the water quality, and the time and distance required for complete mixing.

General:

In the collection of water samples, the sample must be collected below the surface film of the water. Parameters of concern may be concentrated in the surface film and bias a sample high. If the parameter of concern (e.g. oil and grease) is to be collected from the surface, then the QAPP or SAP shall indicate that the surface film will be collected to determine the concentration of floating contaminants (less dense than water).

1.3.3 Required Sample Volumes and Containers

The volume of each sample obtained should be sufficient both to perform all required analyses and provide an additional amount to allow for field QC, laboratory QC needs (e.g. matrix spikes and duplicates), or repeat analyses. The volume of sample required by the laboratory may depend on the analyses to be performed, the sample matrix, the method chosen, the QC requirements, and perhaps the laboratory SOPs. The analytical method typically prescribes the required minimum sample volume, and the method often specifies the ratio of laboratory QC samples per investigative samples needed. If minimum sample volumes are not specified in the analytical method, contact the Sample Broker, in the Quality Assurance Program, in Region VIII or a chemist for assistance. Not all analytical methods have built-in laboratory QC sample requirements, therefore the QC requirements need to be specified in the work agreement (e.g., contract, plans, etc.). Additional information on the required QC samples is provided in Section 1.3.8.

Sample bottles should never be allowed to heat up before or after filling, such as by allowing them to sit in the sun. Volatile Organic Constituents (VOC) vials in particular should be kept cool before the sample is collected to prevent degassing of trace amounts of volatile components from the water when it contacts the warm containers. The type of sample container is dictated by the analyses required. Standard sample containers required for hazardous waste investigations are identified in Table 1 for aqueous materials, and Table 2 for soils and solids. This information is from Table 2-21 and 4-1, respectively, of "Test Methods for Evaluating Solid Waste Physical/Chemical Methods" (EPA SW-846, 1992). Required sample containers for aqueous sampling under non-hazardous programs are listed in Table 3, taken from 40 CFR 136.3(b) Table II.

1.3.4 Sample Preservation and Holding Times

Because few analyses take place at the sampling site, samples generally require preservation before submission to the laboratory for analysis. Preservation is achieved through the addition of chemicals (commonly nitric, sulfuric or hydrochloric acid, sodium hydroxide) and/or by chilling to 4° Celsius (39° Fahrenheit). Samples for some analyses are always preserved to maintain their integrity, and others are preserved to extend the holding times. The sample holding time is the maximum allowed elapsed time between sample collection and initiation of laboratory processing that can result in accurate analytical results. Preservation techniques and sample holding times for all environmental samples collected under hazardous waste programs are listed in Table 1 for aqueous samples, and Table 2 for soils and solids. Required preservation techniques and holding times for routine samples collected under non-hazardous programs are listed in Table 3. Holding times for the toxicity characteristic leaching procedure (TCLP) are provided in Table 4. (Note: the holding time for a composite sample starts after the last aliquot is collected)

All samples requiring preservation should be preserved in the field after the medium is placed in the sample container, prior to sealing and labeling. When grab sampling, preservation must be performed immediately upon collection; laboratory-prepared containers can be used. When composite sampling, sample preservative must be available at the time the initial portion of sample

is obtained and for all subsequent proportional parts. If chemical preservatives are handled in the field, care must be taken not to contaminate other samples with preservatives intended for a specific sample.

Preservation techniques differ for soils and liquids, and vary according to the requested analysis. Soil samples are preserved by chilling to 4°C, and not by addition of acids or other chemicals. Water samples may be preserved by chilling to 4°C, and by addition of acids or other compounds as listed in Tables 1 and 3. Several examples of preservation techniques for specific liquid analyses are described in the following paragraphs:

When the liquid sample to be preserved is contained in a bottle with headspace, (i.e., not VOC vials) the acid or base is added at the calculated proportion to achieve the desired pH (Tables 1 and 3), after the sample has been collected. The bottle is then capped and gently rotated to disperse the acid through the sample. If the buffering capacity of the sample is unknown you will have to check the pH of the sample, after preservation. After the acid or base and sample are mixed, the bottle is uncapped, and narrow range pH sensitive paper is used to check the pH of an aliquot of the sample. Additional acid or base is added if needed, and the sample is then mixed and rechecked for pH. (Note: If your samples contain residual chlorine then you may need to add sodium thiosulfate, see Tables 1-3.)

Suspended solids in samples can produce biased results due to their affinity for metal ions, therefore, when liquid samples for dissolved metals analysis are collected, the samples must be preserved with acid after they are filtered. If any total metals analysis is to be conducted, acid is added directly to the sample and no filtration is conducted.

Samples that should not be chemically preserved in the field are as follows:

- Samples collected within a hazardous waste site that are known or thought to be highly contaminated with toxic materials. Barrel, drum, closed container, spillage, or other source

samples from hazardous waste sites are not to be preserved with any chemical. These samples may be preserved by placing the sample container on ice, however caution should be exercised as the cold may induce a adverse chemical reaction (e.g. crystallization and/or stability changes.)

- Samples that may generate potentially dangerous gases, if they were preserved using the chemicals listed in Tables 1 and 3 (e.g. mining or plating wastes.)

All samples preserved with chemicals shall be clearly identified by indicating on the sample tag that the sample is preserved and with which chemical. If samples normally requiring preservation are not preserved, field records shall indicate why, and an addendum to the QAPP and/or SAP must be completed. Any major deviation from the approved QAPP or SAP must be documented and approved by the EPA Project Manager, as discussed in Section 1.2.1. Preserved samples, if being transported by common carrier, may be governed by DOT hazardous materials regulations for shipping. For example:

- Samples for metals analyses that are shipped by air cannot be preserved with nitric acid in excess of the amount allowed by Department of Transportation (DOT) regulations regarding the transport of hazardous materials. DOT regulations are provided in 49 CFR 171-177. Other pertinent EPA requirements are described in EPA-330/9-78-001-R, "NEIC Policies and Procedures" manual, table C-1; see Table 6, this document.
- Samples for volatile organic compounds analyses which are shipped by air cannot be preserved with hydrochloric acid in excess of the amount allowed by DOT regulations regarding transport of hazardous materials. DOT regulations are provided in 49 CFR 171-177.

Always check with the shipper as their requirements may be more stringent than DOT's.

1.3.5 Calibration of Field Instruments

The calibration process is necessary to ensure that the instrument is working properly, and that the results are within the range of acceptability as determined by the manufacturer's specifications. Calibration data are recorded in a bound field notebook to maintain a record of the calibration for later challenges and proof of acceptability.

All instrumentation used in field activities must be calibrated prior to field use and periodically during use. The minimum requirements for frequency of calibration are based on the manufacturer's recommendations and acceptance criteria defined through the DQO process. More frequent calibration is commonly necessary, depending on the reliability and inherent stability of the instrumentation, extreme field conditions (weather/climate), continuous or heavy use, or high concentrations of monitored parameters.

Field instruments should be calibrated and operated in areas unexposed to temperature and humidity extremes, if possible. Calibration standards should be stored in a manner such that large temperature fluctuation do not occur, because certain parameters (e.g. pH and specific conductance) will vary with temperature.

Continuous sampling devices must be calibrated according to manufacturer's specifications at the time of field set-up, and checked as often as necessary. Depending on the instrumentation, it may be necessary to check and clean the equipment on a routine basis and re-calibrate as necessary. Sample lines for continuous devices must be cleaned or replaced prior to each installation and periodically thereafter. These device may be either temporary or permanent installations.

In those instances where field equipment will not calibrate, attempts should be made to repair the affected equipment. The field manager is responsible for ensuring that spare parts and other appropriate items for field equipment are available for field repairs and to minimize equipment down time. To the extent practical, backup field equipment should be available.

All equipment calibration information must be recorded in permanent ink in a permanently bound logbook assigned to the specific instrument, or in a permanently bound field logbook assigned to the site and project where the equipment is in use. Instrument calibration information must be entered into these logbooks at all times. The calibration information to be recorded includes the date and time of calibration, method of calibration, standards used for calibration, person or persons performing the calibration, results of calibration attempt, and additional comments if the attempt was unsuccessful. Also included should be any recommendations regarding more frequent or less

frequent calibration, equipment maintenance and repair needed, or changes to the calibration procedures or standards used. If any changes are made to entries in any bound logbook, a single horizontal line must be drawn through the old entry. The individual making the alteration must then initial and date the change, and incorporate any additional entries.

NOTE: Calibration standards must be traceable to nationally recognized standards, such as NIST and documentation demonstrating traceability must be kept on file.

All instrument logbooks returned from the field should be examined for maintenance/repair recommendations, and the instrumentation checked for proper operation by the field manager or a designated individual. Any necessary maintenance should be performed immediately to assure instrumentation is in operating condition prior to the next use. All maintenance and repairs performed will be entered into the logbook(s) with the name of the individual(s) doing the work.

1.3.6 Field Equipment and Collection Procedures

The appropriate use of gloves and sample handling to prevent cross-contamination of samples is described below.

- A clean pair of new, disposable non-contaminant contributing (powderless) gloves shall be worn at each sampling location and shall be donned immediately prior to collection of each sample. Gloves must be changed immediately after handling potentially contaminated equipment, etc.
- If possible, one member of the field team should take notes and fill out sample tags, etc., while the other members collect all the samples.
- All surfaces used for sample preparation or field measurement should be covered with waterproof plastic. This procedure is normally used during well sampling events.

The use of appropriate sample containers and the configuration of the sampling area requires consideration of the following items:

- Sample containers must be appropriate for the sampled analytes.

- All sample containers must be properly precleaned before collecting samples.
- Sample containers constructed of plastic shall not be used to collect samples for trace organic compound analyses. Samples for organic analyses should be collected in glass containers with teflon lined caps.
- Sample containers filled with source samples or samples suspected of containing high concentrations of contaminants shall be placed in separate plastic bags immediately after collecting, preserving, tagging, and labeling the sample container.
- PCBs, oil and grease, phenols and hazardous waste samples should be taken directly with the sample container if possible. If collection equipment is needed for PCBs or hazardous waste, one-time-use equipment should be used.
- Sample collection and packaging should be conducted upwind of any internal combustion engines at the sampling site, even if the engines are not operating. The volatiles in petroleum based fuels can contaminate samples collected for VOC analysis.
- If a 12 volt automobile battery is used to power pumps, filters or other sampling equipment, the battery must be located as far from the sample collection and preparation area as is practical. Batteries produce H_2S gas that can contaminate samples collected for VOC analysis.

If background or uncontaminated samples will be collected from a site in addition to samples that are expected to be contaminated, the following precautions should be considered:

- Separate collection equipment (buckets, automatic sampler, shovels, bailers, coring tools, etc.) should be used in background/uncontaminated sample areas and in suspected or known contaminated areas. Where this is not possible or practical, sampling should progress from the uncontaminated areas to the contaminated areas, with thorough decontamination between each area and all sample locations. This reduces the chance of the unintentional cross-contamination of samples from uncontaminated areas, through the use of contaminated sampling equipment. The procedure of collecting samples from the least contaminated area to the most contaminated area (if known) applies primarily to soil and groundwater sampling. This should be a consideration in all sampling, however, in the case of ambient water, rivers and streams, the sampling must start the most downstream station

and progress upstream. This procedure ensures that the samplers are not collecting additional sediments that they may have disturbed by wading into the water course. Background/uncontaminated or control samples in this case are generally taken from the furthest upstream location that will be least affected by any contaminants of concern.

- Unknown waste samples (barrel, tanks, etc.) or highly contaminated media (e.g. product spills) shall never be placed in the same ice chest as samples with low concentrations (ambient or environmental).

1.3.7 Sample Handling and Mixing

After collection, all sample handling should be minimized to avoid affecting the composition and character of the samples. Field personnel should use extreme care to ensure that samples are not contaminated by other samples, by environmental or climatic conditions or media, or by preservatives not intended for those samples. If samples are chilled in an ice chest, personnel should ensure that melted ice cannot cause sample containers to become submerged, as this may result in sample contamination. Sample containers should be sealed in a plastic bag within the cooler to avoid this problem. The cooler should be filled with a sufficient amount of ice before samples are added, so that sample bottles will begin to chill immediately. "Blue ice" may be used if it can be kept frozen in an electric on-site freezer located in a field trailer or other structure at the site. If a freezer is not available, regular bagged ice should be used.

After a sample has been collected, it may require splitting into separate containers for different analyses or preparation of field replicates or splits. Preparation of splits from water samples and soil samples is described in the following sections:

1.3.7.1 Water Sample Splits and Replicates

Water samples collected for VOC analyses must not be split by stirring or transferring from a larger container to smaller containers. These actions can cause "degassing" or volatilization of the

compounds of interest from the samples. Section 1.3.7.3 provides more information on sampling for VOCs.

Ground water collected from a well after the well is properly purged is generally homogenous with low turbidity, and field replicates and splits are more easily prepared than for surface water samples. Multiple ground water samples and field replicates are prepared from subsequent flows or pours as described for the VOC samples in Section 1.3.7.3. Equivalent splits or replicates are prepared by pouring through a device that splits the flow into two streams. The individual streams are then directed into separate sample containers.

Surface water may be less homogeneous than ground water because of the possible presence of sediments and biological materials, and therefore requires specific steps to prepare equivalent replicates and splits. The recommended method for preparing split surface water samples is to continually agitate the sample contents and alternately siphon or pour into respective sample containers. Agitation of the sample will result in degassing and loss of volatile constituents. Please see Section 1.3.7.3 for a description of VOC sampling.

1.3.7.2 Soil Sample Splits and Collocated Samples

Truly equivalent field duplicates of soil, sediment, or sludge samples cannot be collected in the field due to the heterogeneous nature of these media. However, collocated soil samples can be collected. Except for samples to be analyzed for VOCs, it is extremely important that a sample be mixed thoroughly to ensure that all portions of the sample are as homogeneous as possible. The sample should be collected and placed in a stainless steel bowl. Once a sufficient volume of sample is collected, the sample should be mixed by stirring the material in a circular motion or fashion and occasionally turning the material over. The sample is then transferred to the sample containers using a plastic or stainless steel spatula.

To prevent volatilization and loss of the chemicals of interest, soil and sediment samples collected for VOCs analyses must never be mixed as described above. Section 1.3.7.3 describes the procedures for collecting soil samples for VOC analysis.

1.3.7.3 Sampling for Volatile Organic Compounds

Water or liquid samples to be analyzed for VOCs are collected in 40-ml septum vials with screw cap and Teflon-silicone disk in the cap to prevent contamination of the sample by the cap. The vials can be pre-preserved by the laboratory with four drops of concentrated HCL and should be completely filled in the field with the sample medium to prevent volatilization during transport.

The VOC vials can also be preserved in the field by adding appropriate acid per the required analytical method, to a pH of < 2 . Care should be taken to avoid rinsing out the preservative with the sample water. If the sample is not preserved with acid, the holding time (to extraction) is reduced from 14 days to 7.

Field replicate samples or field splits for VOC analyses are prepared by filling vials directly from the sample collection device, and from subsequent flows from the sampling device. The use of bailers is discouraged for sampling volatiles in ground water. If a bailer is used, it should be bottom loading with a stopcock. The sample should be allowed to flow down the inside of the tilted vial to minimize turbulence that could produce volatilization. Gently pour the last few drops into the vial as the vial is leveled out to a vertical position, so that surface tension holds the water in a "convex meniscus." The cap is then gently placed on the vial, and tightened. Although some overflow may occur, air space in the bottle is eliminated.

After capping and tightening the cap, invert the bottle and tap it to check for bubbles. If any bubbles are present, discard this sample and repeat the procedure. If the VOC vials are pre-preserved with acid, they can not be re-used unless acid for preservation is available in the field.

Extreme caution should be exercised when using the vial to collect surface water samples directly from the surface water body to prevent loss of the preservative(if the vial is pre-preserved). When collecting water samples for volatile organic compounds, two 40-ml vials should always be collected for each sample.

When collecting soil and sediments for VOC analysis, 4 oz. glass jars with teflon lined screw caps should be used. A spatula or spoon is used to collect the sample which is gently placed and compressed into the jar. Each jar should be completely filled with minimal head space remaining in the container.

Trip blanks shall be prepared for shipment with both liquid and solid VOC samples (see section 1.3.8.).

1.3.8 Collection of Quality Control Samples

All field sampling programs require the collection of additional samples to provide Quality Control (QC) for the field or laboratory procedures. These include background/control samples, field duplicates, trip blanks, equipment rinseate blanks, several kinds of field blanks, and performance evaluation samples. A description of each of the various QC sample types is provided below.

Background/Control samples are samples collected from the same medium outside of the known area of contamination, under conditions as similar to conditions in the contaminated area as possible. Background samples are generally collected in upgradient areas for ground water and subsurface soil samples, in upstream locations for surface water, and in upwind areas for surface and shallow subsurface soil samples and air samples.

Field duplicate samples are independent (two separate) samples of the same medium collected at the same time from the same location. True duplicate samples, to ascertain field precision,

can only be taken from a open water sample location. Other "duplicate" field samples should be identified as collocated, as in the case of most soil and air samples.

Trip blanks are required only when samples are collected for analysis of VOCs. They are prepared from analyte-free water by the laboratory, and are transported to the sampling site with the VOC sample bottles for the investigative sampling. They are kept with the investigative samples throughout the sampling program and are shipped for analysis with the investigative samples. They are not opened on site, and are designed to evaluate VOC contamination encountered within the coolers during the shipping and handling procedures. Trip blanks are prepared in 40 ml VOA vials with teflon septum lids, and must be chilled and handled in the same manner as a water sample for VOC analysis. Two trip blank vials per each shipping container or cooler containing VOC samples are required. Trip blanks are required both for water and solid media sampling. If field samples are acidified, the trip blanks shall be acidified with the same acid batch before leaving the laboratory. (Note: the field samplers will have to provide the laboratory with the acid unless they are getting their acid from the laboratory.)

Equipment blanks or Rinse blanks are obtained from the last rinse of analyte-free water during decontamination of sample collection equipment. No extraordinary decontamination procedures should be followed when a rinse blank is collected. The date and time of collection should be noted, as well as the ID number of the investigative sample collected just prior to decontamination, and the ID number of the next sample collected with the decontaminated equipment. If dedicated equipment is used, rinseate samples need not be collected.

If contamination is detected in a rinse blank, extensive resampling may be required, based on the rate of rinse blanks collected. (e.g. 20 locations resampled if rinse blanks are collected at the rate of 1 per 20 samples; 10 locations resampled if rinse blanks are collected at the rate of 1 per 10 samples.)

The term Field blank no longer defines a single type of QC sample, due to misuse and misidentification of other types of blank samples. The original definition of "field blank", according to SW-846, was a sample prepared in a VOA vial in the field from analyte-free water, and intended to indicate the presence of VOC contamination in the air at a contaminated site. The term "field blank" must always be defined when used, and usages with other definitions are discouraged.

A Performance Evaluation (PE) Sample is a sample with known concentration of a target analyte, that is sent to a laboratory for blind analysis. The performance of the laboratory is tested by comparing the known values with the laboratory results.

Table 5 summarizes the minimum rate at which QC samples must be collected. PE samples must be submitted for analysis "blind", meaning they should not be identified to the laboratory as QC samples. Other QC samples should be submitted "blind" if possible. The PE samples should be identified with the number of a nonexistent location that is similar to, but different from the other locations at the site. All other labeling should be identical to the investigative samples. The true identity of the PE samples should be recorded in the field logbook, but not on the chain-of-custody form or sample labels and tags that are sent to the laboratory.

1.4 SAMPLE IDENTIFICATION AND CHAIN OF CUSTODY

1.4.1 General

Prior to shipping any samples, the field manager must classify the samples collected as either environmental or hazardous materials samples. In general, environmental samples include drinking water, most ground water and ambient surface water, soil, sediment, treated municipal and industrial wastewater effluent, biological specimens, or any samples not expected to be contaminated with high levels of hazardous materials.

Due to the possible evidentiary nature of all the samples collected during investigations, possession must be traceable from the time the samples are collected until the data or the samples are introduced as evidence in legal proceedings. The use of sample tags to assign a distinct ID number to each sample is described in Section 1.4.2. Appropriate documentation of in situ field measurements is described in Section 1.4.3. Chain-of-custody procedures are summarized in Sections 1.4.4 and 1.4.5. Documentation of all field activities is described in Section 1.5.

1.4.2 Sample Identification Requirements

The minimal requirements for the use of sample tags are described below. Samples and physical evidence collected are identified by a sample tag that is attached to the sample container. An example of a sample tag is included as Exhibit C, following the Section 1.0 tables. All samples should be placed in the proper sample containers and preserved in accordance with applicable procedures described in Tables 1, 2 and 3, and identified with sample tags before being transported off-site. Sample tags are ordinarily attached to the sample jar or container, but in some cases, particularly with biological samples, the sample tags may have to be included with or wrapped around the sample itself. Sample tags shall be completed using waterproof ink and may be partially filled out before the sample is collected. The sample tags are sequentially numbered and are

accountable documents once they are completed and attached to a sample or other physical evidence. The following information shall be included on the sample tag:

- Project/site code - A three digit number assigned by EPA (if applicable)
- Station Number - The sample identification number composed of the project or site code, the sample station location number as specified in the sampling plan, an alphabetic abbreviation for the sample type or medium (ground water, soil, surface water, etc.), and a three digit code indicating sampling event, sequence or depth.
- Station Location - Sampling site location number assigned in the sampling plan.
- Date - A number indicating month, day, year (mm/dd/yy)
- Time - A four-digit number (military time)
- Designation - Grab or composite sample
- Sampler's Signature - Signature of person(s) collecting sample
- Tag Number - A unique serial number stamped on each tag that identifies the Region and has a consecutive number (i.e., 8-1239)
- Preservative - Whether the sample is preserved or unpreserved and the type of preservation
- Type of Analyses - Type of analyses to be conducted on the sample
- Remarks - Significant observations regarding appearance, odor or other physical characteristics of the sample.

The station number is assigned by the field manager or project manager. This number is ordinarily a combination of the project or site code, an alphabetic abbreviation of the medium sampled, a

sample location number, and a three digit numerical code indicating the sampling event or sample sequence (in the case of samples from multiple depths at the same location). For example, a site ID number for the Abercrombie Widget Company might be 404. A surface soil sample would be identified as SS. The location of the sample might be identified as 15, and the second sampling event at the site would be indicated by 002. The complete field sample station number for the surface soil sample described would be 404-SS-15-002. Each separate sampling or monitoring location must have a different alpha-numeric designation. The station number does not have to be as descriptive as above, however the number has to be unique to the location.

Frequently, surface water and sediment samples are collected from the same sampling station and could have the same numerical designation. In this case, the two samples would be distinguished by their labeling with an SW and an SD, respectively. Likewise, ground water (GW) and subsurface soil/deep boring (DB) samples could be distinguished when collected from the same location. Soil samples may be collected from several depths while drilling a soil boring, and these must be distinguished from each other with the use of the three digit sequence code, and from ground water samples subsequently collected from the well installed in the boring.

The field manager and field sampler shall exercise caution to ensure that station numbers and sample numbers are not duplicated during investigations or studies. The exact description of all sampling stations associated with field identification or sample and station numbers shall be documented in the field logbook.

If a sample is split with a facility, state regulatory agency, or other party representative, sample tags or labels with identical information should be attached to each of the split sample containers. Sample tags shall be completed, marked "split", and attached to each split sample. The split sample shall also be identified on the Chain-of-Custody Record and in the field notebook.

When samples are collected from vessels or containers which can be moved (e.g., barrels) or from a portion of an on-site structure, the field investigator shall mark the container or structure with the

field identification or sample station number for future identification, if necessary. The container or structure shall be marked by utilizing a permanent marker pen or spray paint, but should not be marked if it already has a unique marking or serial number. If unique serial or ID numbers are present, these numbers shall be recorded on the sample tag and in the field logbook. In addition, it is suggested that photographs be taken of any container that samples are collected from and the necessary information recorded in the field logbook.

1.4.3 In situ Field Measurements

Forms and records that report the results of in situ measurements collected do not require a sample tag. When in situ measurements are made the data are recorded directly in field logbooks or field sample records (FSRs) with identifying information (project/site code, sample numbers, station numbers, date, time, samplers, field observations and remarks). Examples of in situ measurements include temperature, pH, specific conductance, flow measurements, geophysical measurements, surveying measurements, continuous air monitoring, etc.

In the case of well sampling, in situ field measurement are made continuously until certain acceptance criteria/performance standards are met. That is, pH, temperature and conductivity are continuously measured during purging until stability is obtained. Stability measurements start after the first casing volume has been removed. The turbidity is also measured during the purging until the data, nephelometric turbidity units (NTUs) are less than 10. When these acceptance criteria are met, sampling can begin. By using these criteria, purging time may be reduced.

If recorder and/or instrument charts are obtained from facility-owned analytical equipment such as flow recorders, the following information should be written on the charts.

- The starting and ending time(s) and date(s) for the chart;
- A description of the location being monitored and any other information required to interpret the data such as type of device, chart units, etc.
- The field investigator's initials; and
- Results of an instantaneous measurement of the media being measured by the recorder. The instantaneous measurement shall be entered at the appropriate location on the chart along with the date and time of the measurement and the field investigator's initials.

After the chart has been removed, the field investigator shall indicate on the chart from whom the chart (or copy of the chart) was received, and will enter the date and time, as well as the investigator's initials.

1.4.4 Sample Custody

1.4.4.1 Definition and Required Documentation

A sample or other physical evidence is under custody if:

1. It is in your possession;
2. It is in your view after being in your possession;
3. It was in your possession and then you locked it up or placed it in a sealed container to prevent tampering; or
4. It is in a designated secure area.

The field Chain-of-Custody Record is used to record the custody of all samples or other physical evidence collected for Region VIII EPA. The Chain-of-Custody Record also serves as a sample logging mechanism for the Region's sample custodian. Region VIII EPA uses three types of Chain-of-Custody Record forms : 1) Organic Traffic Report and Chain-of-Custody Record, 2) Inorganic Traffic Report and Chain-of-Custody Record for the Contract Laboratory Program (CLP) and 3) a Chain-of-Custody form for transmitting custody of non-CLP samples and all samples sent to the Region VIII Laboratory. An example of a chain-of-custody form is included as Exhibit D, following the Section 1.0 tables. These forms are not to be used to provide a receipt for samples where there is a legal requirement to document the collection of split or duplicate samples. Section 1.4.5 addresses the use of receipts to document collection of samples.

The Chain-of-Custody Record is a serialized, multi-carbon document. Once the Record is completed, it becomes an accountable document and must be maintained in the project file. The suitability of any other form for chain-of-custody should be evaluated prior to use, based upon its inclusion of similar information in a legible format.

1.4.4.2 Field Custody Procedures

- To simplify the Chain-of-Custody Record and eliminate potential litigation problems, as few people as possible should handle samples.
- Sample tags shall be completed for each sample (as discussed in Section 1.4.2), using waterproof, non-erasable ink.
- If possible, the field sampler should keep the samples in his/her continuous custody from the time of collection until they are delivered to the laboratory analyzing the samples. If this can not be accomplished, the samples must be placed in a container that is sealed with an EPA custody seal (Exhibit E, following the Section 1.0 tables). The field sampler shall write the date and his/her signature on the seal. It is not practical to seal individual sample bottles.

- A Chain-of-Custody Record will be completed for all samples or physical evidence as specified in Section 1.4.4.1. A separate Chain-of-Custody Record will be utilized for each final destination or laboratory utilized during the inspection or investigation.
- The field manager and/or the field sample custodian is personally responsible for the proper handling and custody of the collected samples until they are properly and formally transferred or dispatched to another person or facility.
- The field manager is responsible for determining if proper custody procedures were followed in the field and if additional samples are required.
- Physical evidence such as video tapes, documents or other small items shall be placed in sealable plastic bags or envelopes. An EPA custody seal should be affixed so that they cannot be opened without breaking the seal. A Chain-of-Custody Record shall be maintained for these items. Any time the custody seal is broken, this shall be noted on the Chain-of-Custody record, and a new seal shall be affixed. The information on the seal shall include the field investigator's signature, as well as the date of sealing.
- In general, Region VIII EPA personnel shall not accept samples from other sources unless the sample collection procedures used are known to be acceptable, can be documented, and the sample Chain-of-Custody can be established. If such samples are accepted by Region VIII personnel, standard sample tags containing all relevant information and the Chain-of-Custody Record shall be completed for each set of samples.

1.4.4.3 Transfer of Custody and Shipment

The transfer of custody is an important aspect of Chain-of-Custody. The procedures listed below must be followed.

- When transferring the possession of samples, the individuals relinquishing and receiving the samples will sign, date, and note the transfer time on the record. This record

documents sample custody transfer from the sampler, often through another person, to the analyst in a laboratory. All shipments will be accompanied by the Chain-of-Custody Record identifying its contents. The original record will accompany the shipment and a copy will be retained by the team leader to be placed in the project files. If samples are hand delivered to the laboratory the samplers will receive a copy to the Chain-of-Custody form from the laboratory custodian.

- Whenever samples are split with a facility or government agency, it is noted on the Chain-of-Custody Record. The note is signed by both the field sampler or team leader and the recipient in the box named "split samples". If the split is refused, this will be noted and signed by both parties. The person relinquishing the samples to the facility or agency should request the signature of a representative of the appropriate party, acknowledging receipt of the samples. If a representative is unavailable or refuses to sign, this is noted in the "Remarks" space. When appropriate, as in the case where the representative is unavailable, the Chain-of-Custody Record should contain a statement indicating that the samples were delivered to the designated location at the designated time and date.
- If sent by mail, the package will be registered with return receipt requested. If sent by common carrier, the carrier's name and other pertinent information are entered on the Chain-of-Custody Record in the transfer of custody fields (e.g. IN TRANSIT VIA FED. EX.).

Prior to shipping any samples, the field manager must classify the samples collected as either environmental or hazardous materials samples. Guidance for complying with US Department of Transportation (DOT) regulations in shipping is given in 49CFR Parts 171-177. Depending on the amount of preservative added to a sample, some samples may be considered as hazardous materials and must be shipped in accordance with procedures described in the current US DOT Regulations (see Table 6). Also check with the shipper as they may have more restrictive requirements.

Samples collected from process wastewater streams, drums, bulk storage tanks, soil sediment, or water samples from areas suspected of being highly contaminated may require shipment as

hazardous materials. The transportation of hazardous materials by EPA personnel is covered by EPA Order 1000.18. If a sample is collected of a material that is listed as a dangerous good, then that sample must be identified, packaged, marked, labeled, and shipped according to the instructions given for that material. No samples may be offered for transport without DOT hazardous materials markings and labels if the composition is unknown or only partially known, yet the project leader knows or suspects that they may contain hazardous materials.

Samples shall be properly packaged for shipment and dispatched to the appropriate laboratory for analysis with a separate Chain-of-Custody Record accompanying each shipment.

Samples collected and designated as environmental samples shall be packed prior to shipment using the following procedures:

- Select a sturdy cooler in good repair (i.e. does not leak and has secure closure.) Secure and tape the drain plug with fiber or duct tape. Line the cooler with a large heavy duty plastic bag.
- Be sure the lids on all bottles are tight and will not leak.
- Place all sample containers into the large heavy duty plastic bag. Wrap each glass bottle with bubble wrap if possible. Securely fasten the top of the large plastic bag with tape. A signed and dated custody seal must then be placed around the top of the plastic bag, over the tape. If the shipping container has a smooth surface that the seal will stick to, sealing the plastic bags with a seal is optional.
- Put "blue ice" (or ice that has been placed in heavy duty polyethylene bags and properly sealed) on top of or between the samples.
- To meet refrigeration requirements, the temperature in a cooler must be measured and documented prior to shipment and upon receipt of the samples at the laboratory. Another option is to safely pack a min-max thermometer within the cooler, and record the temperatures upon opening the cooler at the laboratory.

- Place the Chain-of-Custody Record into a plastic bag, tape the bag to the inner side of the cooler lid, and then close and securely tape the cooler lid shut.

A laboratory custodian or clerk should receive and check all samples against the Chain-of-Custody Record, when the samples arrive at the laboratory and then place them in a secure area.

1.4.5 Sample Receipts

The Resource Conservation and Recovery Act (RCRA), Toxic Substances Control Act (TSCA) and Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) require that a "receipt" for all facility samples collected during inspections and investigations be given to the owner/operator of each facility before the field sampler departs the premises. Receipts are generally not used on Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites because the owner/operator is rarely on site when sampling is conducted.

A Receipt for Samples Form (Exhibit F, following Section 1.0 tables) will be required to satisfy the receipt for samples provisions of RCRA TSCA and FIFRA. This form also documents if split samples were required and if they were provided to the owner/operator of the facility or site being investigated.

The copy of the Receipt for Samples Form is to be given to the facility or site owner/operator. The original copy of this form must be maintained in the project file for the facility/site.

1.5 FIELD RECORDS AND DOCUMENTATION

1.5.1 Purpose

Documentation establishes procedures, identifies written records, enhances and facilitates sample tracking, standardizes data entries, and identifies and establishes authenticity of the sample data collected. Proper documentation also provides the following:

- Ensures that all essential and required information is consistently acquired and preserved;
- Documents timely, correct, and complete analysis;
- Satisfies quality assurance requirements;
- Establishes Chain-of-Custody;
- Provides evidence for court proceedings; and
- Provides a basis for further sampling.

1.5.2 Field Records

Appropriate field records written in a bound field logbook or on data sheets must be completed at the time of sample collection. Bound logbooks are required for CERCLA investigations, and are highly recommended for other site investigations, including RCRA.

The bound field log book or daily log sheets must be maintained by the field personnel to provide a daily record of significant events. The field logbook should be constructed such that pages cannot be removed without tearing them out and pages should be numbered as they are filled. Preferably,

field logbooks should be dedicated to an individual project. In general, field logbooks as well as field records should provide the following information:

- Record, identify, and describe all pertinent sampling and monitoring activities;
- Record quantitative and qualitative information for each sample collected; and
- Record and describe any team activities, including observations and events.

The investigator's name, project name, and project code should be entered on the inside cover of the logbook. All entries should be signed and dated with the time of entry recorded, and each page must be initialed and dated. At the end of each day's activity, or entry of a particular event, if appropriate, the investigator should draw a diagonal line on the page below the last entry, and initial and date the line.

All aspects of sample collection and handling as well as visual observations shall be documented in the field logbooks. All sample collection equipment, field analytical equipment, and equipment utilized to make physical measurements shall be identified in the field logbooks, by serial number where appropriate. All calculations, results, and calibration data for field sampling, field analytical, and field measurements and analyses must be traceable to the specific piece of field equipment utilized and to the field investigator collecting the sample, making the measurement, or performing the analyses.

All entries in field logbooks shall be legible, and shall contain accurate and inclusive documentation of all project activities. Because field records are the basis for later written reports, language should be objective, factual, and free of personal feelings or other terminology which might prove inappropriate. Once completed, field logbooks become accountable documents and must be maintained as a permanent record in the project files.

In a legal proceeding, notes, if referred to, are considered part of the administrative record and are admissible as evidence and subject to cross-examination.

1.5.3 Photograph Identification

All photographs taken by field personnel shall be identified on the back of the print with the following information:

- An accurate description of what the photograph shows, including the name of the facility or site and the location;
- The date and time that the photograph was taken, the filter type (if any), film speed and F stop;
- The orientation of the photograph (i.e., looking northeast, etc.); and
- The signature of the photographer.

If the photograph is taken with a Polaroid camera, the information shall be entered on the back of each photograph with an indelible marker as soon as the photo is taken. If a 35 mm camera is used, a serial type record of each frame exposed shall be kept in the field logbook along with the information required for each photograph. The field investigator shall enter the required information on the prints, using the serialized photographic record from the field logbook, and the numbers on the negatives to identify each photograph. For criminal investigations, negatives must be maintained with the field logbook in the project file and stored in a secured file cabinet.

1.6 DECONTAMINATION AND DISPOSAL OF WASTES GENERATED

1.6.1 Requirements for Decontamination

When sampling contaminated soils, sediments, surface water, and ground water, sampling devices and equipment must be carefully cleaned prior to and between each sample collected to avoid cross-contamination between samples. Cross-contamination can be minimized with thorough decontamination as described below, by encasing equipment with disposable outer wrappings (plastic/foil) after cleaning, and by using disposable sampling devices. Analysis of the distilled or deionized (DI) water used for the final rinse must also be conducted unless the water was prepared in a laboratory, however, records of analysis, contaminants of concern, of the laboratory-generated water must be available for review.

Equipment and sampling devices that are relatively inexpensive and easily obtainable can be properly discarded after a single use. However, many of the sampling devices used are expensive and will be re-used, requiring decontamination after each use. When cleanup of contaminated equipment is necessary, it should be done in the field, whenever possible. When equipment becomes contaminated to such an extent that decontamination in the field is not feasible, it should be properly discarded at the site, after proper permission has been obtained, for disposal with other contaminated materials (Section 1.6.5). Ideally, dedicated equipment for each sample location is recommended to reduce the possibility of cross-contamination between locations.

1.6.2 Available Decontamination Methods

Selection of a decontamination method requires consideration of the following items:

- Contaminants present or suspected;

- Effectiveness of different decontamination methods for the specific substances present;
- Health or safety hazards of the decontamination method;
- The location where the decontamination procedures will be conducted;
- The size and types of equipment that will require decontamination;
- The frequency that specific equipment will require decontamination;
- Available methods for containing and disposing of the residual contaminants, cleaning solutions, and rinseate from the decontamination process; and
- The use of a quality control measure, such as equipment blanks or wipe testing, to determine the effectiveness of the decontamination procedure.

Decontamination is the process of neutralizing, washing, rinsing, and removing contaminants from the exposed outer surfaces of equipment and personal protective clothing to minimize the potential for contaminant migration. Decontamination methods either physically remove contaminants, inactivate contaminants by chemical detoxification or disinfection/sterilization, or remove contaminants by a combination of both physical and chemical means. Available physical and chemical decontamination procedures are described below.

Physical removal involves dislodging, displacing, rinsing, wiping off, or evaporation of the contaminants. Removal of gross contamination (visible) should first be attempted by physical means. Loose contaminants can be removed by rinsing with tap, distilled or deionized water. High pressure water or steam is used to remove contaminants that adhere more tightly. Scraping, brushing and/or wiping may also be used before high pressure or steam is used.

Some volatile liquids will be removed by evaporation. Evaporation can be enhanced by rinsing or steam cleaning, followed by a water rinse and exposure to the sun.

Chemical removal involves a wash/rinse process using cleaning solutions. This wash/rinse process should follow the physical removal of gross contamination, if the contaminants are not soluble in water or are present in high concentrations. Surfactants (detergents) are commonly used to reduce adhesion forces and encourage dissolving and dispersal of the contaminant in the detergent. Solvents (including hexane) are used to dissolve selected chemicals that are not soluble in water and are only somewhat soluble in detergents. The solvent selected for clean up cannot be a potential contaminant at the site. Washing with either surfactants or solvents must be followed by a minimum of three rinses with clean tap water and three rinses with deionized or distilled water to remove the chemicals.

A decontamination plan describing the solutions to be employed, and the methodologies to be used to determine the effectiveness of the decontamination shall be referenced or stipulated in detail in a QAPP or site-specific SAP. The use of decontamination rinseate blanks and other quality control procedures serve to document the decontamination process and effectiveness. Disposal of the rinseate from decontamination is different for non-hazardous versus hazardous rinseate. Sections 1.6.5.2 and 1.6.5.3 describe appropriate disposal for nonhazardous rinseate and hazardous rinseate, respectively.

1.6.3 Decontamination of Small Equipment

Hand-held sampling devices and equipment and small samplers used with drilling rigs, such as split spoon samplers, must be decontaminated after each sample is collected. The equipment must be brushed and scraped so that most gross contaminants are removed. The equipment must then be washed with a strong non-phosphate detergent/soap mixture. After all gross contaminants have been removed, the equipment must be rinsed three times with tap water followed by three rinses with deionized water. The equipment must be allowed to air dry thoroughly, in a clean environment.

If the contaminants consist of organic chemicals with low solubility in water and detergents, the equipment must be rinsed with a organic solvent following the tap and deionized water rinses described above. Following the solvent rinse, the equipment must be rinsed three times with tap water followed by three rinses with deionized water, and allowed to dry again. If the constituents of interest are inorganic, the equipment must be rinsed with dilute acid instead of organic solvent.

Site-specific decontamination procedures depend on the contaminants present, and shall be approved by EPA in the QAPP or the site-specific SAP.

A typical decontamination procedure for small equipment includes the following steps:

- 1) Scrape or wipe to remove all visible contamination.
- 2) Scrub with a brush and non-phosphate detergent.
- 3) Rinse three times with potable tap water.
- 4) Rinse three times with deionized (DI) or distilled water.
- 5) If significant concentrations of inorganic compounds are expected, rinse with dilute (10 percent) acid.
- 6) If significant concentrations of organic compounds are expected, rinse with acetone and/or pesticide-quality Hexane.
- 7) Allow equipment to air dry, and wrap in plastic before transporting to the next sampling location. If the equipment will be used to sample for volatiles analysis, it should be wrapped in metal foil rather than plastic.

Rinseate blanks must be collected from the last rinse by DI or distilled water, at a minimum rate of once per day, or once after every 20 decontamination procedures, whichever is more. These rinseate blanks are analyzed for contaminants of concern to verify the effectiveness of the decontamination procedure. Collection of additional rinseate blanks may be desirable if a potential contaminant is particularly difficult to remove from sampling equipment. If laboratory analysis indicates that a single rinseate sample collected for 20 sampling sites is contaminated with a

contaminate of concern, resampling of all 20 locations may be required. Collection of rinseate samples, and the risk of cross contamination can be avoided if dedicated sampling equipment is used.

1.6.4 Decontamination of Large Equipment

Decontamination of drilling equipment and other large formation sampling equipment involves cleaning tools that are used in boreholes or monitoring wells. Drilling equipment should be decontaminated between each borehole. More frequent cleaning should be performed if cross-contamination between vertical zones within a borehole is possible.

The most common and generally preferred methods of drilling equipment decontamination involve either a clean potable water wash, steam cleaning, or a water wash/steam cleaning combination. A non-phosphate detergent is also commonly used.

A sequence for decontamination of low to moderately contaminated equipment should be as follows:

- Water or steam rinse to remove particulates.
- Steam wash with water and non-phosphate detergent.
- Steam or water rinse with potable water.

Additional wash/rinse sequences may be necessary to remove the contaminants completely. A rinseate sample must be taken after every 20 decontamination procedures, or at least once per day, to document the effectiveness of the decontamination procedures. Rinseate samples should be collected more frequently if cross contamination is likely to be a concern (such as at heavily contaminated sites without dedicated sampling equipment). Samplers should be aware that the

specific source of contamination will not be known if a contaminated rinseate sample was collected after numerous sampling and decontamination procedures. All of the locations associated with that rinseate blank may require resampling to identify the error.

Section 3 of the March 1991 "Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells" (EPA 600/4-89/034) should be consulted for a more complete discussion on field decontamination programs and procedures related to drilling and sampling equipment.

1.6.5 Handling of Investigation-Derived Waste

1.6.5.1 Description of Investigation-Derived Waste

All waste materials generated during field investigations at potential hazardous waste sites are known as investigation-derived waste (IDW). Examples of IDW that may require treatment, storage, and disposal are as follows:

- Personnel protective equipment (PPE). This includes disposable coveralls, gloves, booties, respirator canisters, splash suits, etc.
- Disposable equipment (DE). This includes plastic ground and equipment covers, aluminum foil, conduit pipe, disposable bailers, pump tubing, etc.).
- Soil cuttings from drilling or hand augering operations.
- Drilling fluids (mud or water) used for drilling.
- Ground water obtained through well development or well purging.
- Decontamination fluids including spent solvent, detergent water and rinse water.

Some of these waste materials may be hazardous wastes and must be properly disposed in accordance with EPA regulations. The decision as to whether materials are hazardous should be based on the results of sample analyses.

The project leader or site manager should determine the appropriate handling approach upon designating the IDW as either RCRA hazardous or RCRA nonhazardous. (See U.S. EPA "Management of Investigation-Derived Wastes During Site Inspections" EPA/540/G-91-009, 1991.) The project leader or site manager should use the decision tree shown in Exhibit G of this document (following the Section 1.0 tables) for help in selecting the best approach for IDW management, and identifying the steps that are involved in executing the approach. The decision tree summarizes basic elements of planning for IDW handling such as waste minimization, characterization, and management, and indicates when and how IDW should be handled on-site or disposed off-site. Management of IDW must also be described in detail in the QAPP or site-specific SAP.

1.6.5.2 Management of Non-Hazardous IDW

The management and disposal of non-hazardous IDW from all sampling sites should be addressed in the QAPP or site-specific SAP. If PPE and DE is non-hazardous or can be decontaminated and rendered nonhazardous, these wastes should be double-bagged, and deposited either in an industrial dumpster (on-site or at the EPA warehouse), or in a municipal landfill (RCRA Subtitle D facility). Non-hazardous IDW such as soil cuttings, drilling fluids, development or purge water, decontamination fluids, etc. should be left on-site unless other circumstances require off-site disposal. These circumstances include a state ARAR or a high probability of serious community concerns.

At all hazardous waste sites, without adequate information to define the potential waste hazard, the IDW generated should be considered potentially hazardous until the results of testing

indicate otherwise. All drilling, development and decontamination fluids and soil cuttings should be containerized on site until testing to verify that they are not contaminated.

The on-site handling options available when the results of analytical testing indicate that the IDW are nonhazardous, are listed below.

■ For decontaminated PPE and DE:

1. Double bag and deposit in an on-site dumpster, or in any municipal landfill.
2. Dispose of at the site's treatment or disposal unit.

■ For soil cuttings:

1. Spread around the well.
2. Put into a shallow pit above the water table, within the area of contamination (AOC).
3. Dispose of at the site's treatment or disposal unit.
4. If the boring is less than 10 feet deep and did not penetrate the water table, cuttings may be placed back into the boring. All borings deeper than 10 feet or that encountered ground water shall be plugged.

■ For drilling fluids and ground water (development and purge water):

1. Pour onto ground (from containers) downgradient from the well to allow infiltration.
2. Dispose of at the site's treatment or disposal unit.

■ For decontamination and rinse fluids:

1. Pour onto ground (from containers) downgradient from the well to allow infiltration.
2. Dispose of at the site's treatment or disposal unit.
3. Evaporate dilute decontamination fluids on site if placed in an acceptable treatment container.

(Note: Permission must be obtained in writing from the site manager before disposal of any waste on site.)

1.6.5.3 Management of Hazardous IDW

Disposal of hazardous or suspected hazardous IDW from hazardous waste sites should be addressed in the QAPP or site-specific SAP. If IDW consist of hazardous soil cuttings that pose no immediate threat to human health and the environment, then the soil cuttings can be left on-site, with permission of the site manager, within a delineated Area of Contamination (AOC) if they are containerized.

All soil borings that generate soil cuttings determined to be hazardous, must be plugged with cement grout from total depth to within two - three feet below land surface. Cuttings can not be placed in a borehole, regardless of depth, if analysis indicates that the cuttings are contaminated.

If on-site disposal is not feasible, and if the wastes are suspected to be hazardous, appropriate tests must be conducted to make that determination. If they are determined to be hazardous wastes, they must be properly contained and labeled. These hazardous wastes may be stored on the site for a maximum of 90 days before they must be manifested and shipped to a permitted treatment or disposal facility. If possible, the generation of hazardous IDW should be anticipated so that permits for the proper containerization, labelling, temporary storage,

transportation, and disposal/treatment of these wastes can be arranged in accordance with EPA regulations.

IDW should be disposed off-site at a permitted, RCRA subtitle C, TSD facility in the following situations:

- They are RCRA hazardous PPE and DE.
- They are RCRA hazardous soil cuttings that may pose a substantial risk if left on site.
- They are RCRA hazardous drilling fluids; ground water, or decontamination fluids.
- Leaving them on-site would create increased risks at the site.

Planners for off-site disposal of hazardous wastes should consider the following EPA guidelines:

- Incorporate a provision in the site access agreement form to inform the site owner that containerized IDW may be temporarily stored on-site while awaiting pickup for off-site disposal. The agreement should also request the owner's cooperation.
- Initiate the bidding process for IDW testing, pick-up, and disposal. If there are any subcontracting needs in planning the off-site disposal, the means of disposal should be specified. Since RCRA hazardous IDW must go to RCRA hazardous waste disposal facilities that comply with the off-site policy, the site manager should obtain a list of available facilities. Each EPA Region maintains a list of RCRA Treatment, Storage and Disposal (TSD) facilities that meet the conditions of the off-site policy. The site manager must also check the selected facility's compliance before arranging for IDW pick-up. If IDW are RCRA nonhazardous, the site manager must also check if the receiving RCRA nonhazardous waste facility complies with the off-site policy.
- Coordinate IDW generation with testing and pick-up. IDW samples should be collected in accordance with "Test Methods for Evaluating Solid Waste, SW-846," and shipped for RCRA tests (and other tests, if necessary) as early as possible during the site

investigation. IDW need not be analyzed by a CLP laboratory. The site manager should use the laboratory services of the pickup and disposal subcontractor, obtain an EPA ID number and manifest form for RCRA hazardous IDW, and a bill of lading for RCRA nonhazardous IDW.

- Prepare adequate numbers and types of containers. Drums should be used for collecting small amounts of IDW. Larger amounts of soil and water can be contained in Baker tanks, poly tanks, and bins. PPE and DE should be collected in drums for disposal at a hazardous waste facility.
- Designate a storage area (either within the site's existing storage facility, existing fenced area, or within a temporary fence constructed for the site investigation). No unauthorized personnel may have access to the storage area. If a temporary storage facility is to be constructed, its location and size must be agreed upon with the site owner, and all construction materials should be delivered to the site before or on the first day of the site investigation.
- All RCRA hazardous wastes stored on site must comply with the 90 and 180 day storage requirements, as specified in RCRA regulations.
- All hazardous wastes generated at CERCLA sites must comply with requirements specified in the CERCLA and SARA regulations.

Hazardous investigation-derived waste should be kept to a minimum. Many of the above PPE and DE wastes can be deposited in industrial dumpsters if care is taken to keep them segregated from hazardous waste contaminated materials and environmental media. Disposable equipment and some PPE can sometimes be cleaned to render it nonhazardous. The volume of spent solvent waste produced during equipment decontamination can be reduced or eliminated by applying only the minimum amount of solvent necessary.

The reader is referred to "Management of Investigation-Derived Wastes During Site Inspections" (EPA/540/G-91/009) (21) for further guidance on the management and disposal of investigation-derived waste.

1.7 SITE SAFETY CONSIDERATIONS

1.7.1 General

Protecting the health and safety of workers is a major consideration during the execution of any field work. The following information is geared toward safety considerations at hazardous waste sites, but many of the precautions apply to all sampling activities.

The U.S. Occupational Safety and Health Administration (OSHA) has established regulations governing the health and safety of employees engaged in hazardous waste operations and emergency response. The regulations codified at 29 CFR 1910.120, contain general requirements for health and safety programs, site characterization and analysis, site control, training, medical surveillance, engineering controls and work practices, personal protective equipment, exposure monitoring, informational programs, materials handling, decontamination, and emergency procedures. EPA has incorporated these standards by reference into its regulations at 40 CFR 311, however, the actual standards are not reported herein.

All field activities conducted at hazardous waste sites in EPA Region VIII shall be conducted in accordance with the requirements of 29 CFR 1910.120. The requirements are complex, and it is the responsibility of each employee involved in field work to understand and follow these requirements. It is always the responsibility of each field sampler to use common sense and the health and safety equipment/training received. It is the responsibility of the samplers supervisor to make sure that the sampler has all required training and updates before the sampler is allowed to participate in field activities.

EPA has published a document entitled "Standard Operating Safety Guides" (June, 1992, EPA publication no. 9285.1-03) which summarizes topics that include the following: components of a health and safety program, development of a Health and Safety Plan (HSP), required training, site control, personal protective equipment, air monitoring, medical surveillance program, heat stress

and cold exposure, decontamination, drum handling, hazards, confined space entry. Consult this document for explicit guidance on any aspect of health and safety considerations.

1.7.2 Site Specific Health and Safety Plans

A site-specific Health and Safety Plan (HSP) shall be developed for every hazardous waste site project. When there is more than one organization involved at the site, the development of the safety plan should be coordinated among the various groups. The plan for a non-hazardous site will include, at a minimum, the name(s), location(s) and phone number(s) of the local emergency medical facilities.

Before commencing any site activities, field personnel will be required to read the site specific HSP, and sign a statement that they have read and understand the HSP. An on-site meeting will also be held at the beginning of the project, and all field personnel will be briefed on the potential hazards, level of PPE and safety procedures specified in approved site HSP. In addition, the plan's emergency instructions, telephone number and directions to the designated emergency medical facility shall be posted in a conspicuous location at the site command post, and shall be available at each work site. At non-hazardous sites the field personnel will be made aware of the local health facilities and their locations.

An assessment of the potential dangers must be completed to determine the hazards that could affect site personnel. The site HSP must specify the potential hazards and specify the necessary precautions to mitigate the hazards.

Region VIII does not approve or disprove Health and Safety plans. It is the responsibility of every inspector to ensure compliance with 29 CFR 1910.120.

Health and Safety Plans must be submitted as a separate document and not be included as part of a QAPP/SAP. The rationale for this is the potential liability an employee faces if these are approved as part of a QAPP/SAP.

1.7.3 Training of Field Personnel

The required training and medical monitoring for field personnel who work at any field sites, in accordance with 29 CFR 1910.120, is summarized below.

- Medical monitoring physicals (annual renewal if on-site more than 30 days per year).
- 40-hour hazardous waste site training (no renewal required).
- or
- 24-hour non-hazardous waste site training (no renewal required).
- 8-hour site safety refresher training (annual renewal).
- Cardio-pulmonary resuscitation (CPR) certification (annual renewal).
- First aid certification (tri-annual renewal)
- Respirator fit testing (annual renewal or otherwise as required).
Hazardous waste site workers only.

1.8 Standard Operating Procedures

NOTE: *Not all of the following sections have been completed as of 8/96. Those that are complete have the date of issue noted after the title.*

SOIL SAMPLING AND BOREHOLE DRILLING

BOREHOLE DRILLING AND SOIL SAMPLING

SOIL CLASSIFICATION AND LITHOLOGIC LOGGING

SURFACE SOIL SAMPLING

WELL AND BOREHOLE ABANDONMENT

MONITORING WELL INSTALLATION AND DEVELOPMENT

MONITORING WELL DESIGN AND INSTALLATION

WELL DEVELOPMENT JUNE 1994

GROUND WATER SAMPLING, FIELD MEASUREMENT AND AQUIFER TESTING

WELL PURGING JUNE 1994

GROUND WATER SAMPLING

WATER LEVEL AND NAPL MEASUREMENT IN A WELL OR BOREHOLE

SAMPLING OF POTABLE WATER SUPPLIES

AQUIFER TESTING

SURFACE WATER AND SEDIMENT SAMPLING AND MEASUREMENTS

SURFACE WATER SAMPLING

SURFACE WATER FLOW MEASUREMENT

SEDIMENT SAMPLING

BIOLOGICAL, AMBIENT AIR, AND OTHER MEDIA SAMPLING

BIOLOGICAL SAMPLING - TERRESTRIAL

BIOLOGICAL SAMPLING - AQUATIC

AMBIENT AIR SAMPLING

FIELD INSTRUMENTATION AND FIELD SUPPORT MEASUREMENTS

GUIDELINES FOR GEOPHYSICAL STUDIES

SURVEY CONTROL REQUIREMENTS JUNE 1994

1.9 SELECTED REFERENCES AND ACRONYMS

1.9.1 SELECTED REFERENCES

1. U.S. Department of the Interior. 1969. A Practical Guide to Water Quality Studies of Streams. CWR-5.
2. U.S. Department of Energy. 1980. The Environmental Survey Manual. DOE/EH-0053.
3. U.S. Environmental Protection Agency. 1973. Biological Field and Laboratory Methods for Measuring the Quality of Surface Waters and Effluents. EPA/670/4-73-001.
4. U.S. Environmental Protection Agency. 1974. Wastewater Sampling Methodologies and Flow Measurement Techniques. EPA/907/9-74-005.
5. U.S. Environmental Protection Agency. 1977. Quality Assurance Handbook for Air Pollution Measurement Systems. EPA/600/4-77-027a.
6. U.S. Environmental Protection Agency. 1980. Samples and Sampling Procedures for Hazardous Waste Streams. EPA/600/2-80-018.
7. U.S. Environmental Protection Agency. 1981. NEIC Manual for Groundwater/Subsurface Investigations at Hazardous Waste Sites. EPA/330/9-81-002.
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9. U.S. Environmental Protection Agency. 1982. Environmental Monitoring at Love Canal. EPA/600/4-82-030 a-d.
10. U.S. Environmental Protection Agency. 1984. Documentation of EMSL-LV Contribution to the Kellogg Idaho Study. EPA/600/4-84-052.

11. U.S. Environmental Protection Agency. 1985. Quality Assurance Project Plan for the TSCA and FIFRA Investigation Programs. EPA Region VIII. Air and Toxics Division.
12. U.S. Environmental Protection Agency. 1985. Occupational Safety and Health Guidance Manual for Hazardous Waste Site Activities. Publication No. 85-115.
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18. U.S. Environmental Protection Agency. 1989. Soil Sampling Quality Assurance User's Guide. EPA/600/8-89-046.
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20. U.S. Environmental Protection Agency. 1993. The Data Quality Objectives Process for Environmental Decisions. QAMS Draft.
21. U.S. Environmental Protection Agency. 1991. Management of Investigation-Derived Wastes During Site Inspections. EPA/540/G-91-009.
22. U.S. Environmental Protection Agency. 1991. Guide to Management of Investigation-Derived Wastes. Publication No. 9345.3-03FS.

23. U.S. Environmental Protection Agency. 1991. Standard Operating Procedures and Quality Assurance Manual. EPA Region IV. Environmental Services Division.
24. U.S. Environmental Protection Agency. 1992. Standard Operating Safety Guides. June 1992. EPA Publication No. 9285.1-03.
25. U.S. Environmental Protection Agency. 1991. EPA Requirements for Quality Assurance Project Plans for Environmental Data Operations. EPA QA/R-5.
26. U.S. Fish and Wildlife Service. 1989. Decontamination Reference Field Methods. Prepared by USDOE/INEL/EG&G.
27. USEPA Region VIII Quality Management Plan, 1996.
28. NEIC Policies and Procedures Manual, EPA 330/9-78-001-R.

1.9.2 LIST OF ACRONYMS

AC	Areal composite
AOC	Area of Contamination
ARAR	Applicable Relevant and Appropriate Requirements
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CLP	Contract Laboratory Program
DE	Disposable Equipment
DIFW	Depth-Integrated Flow-Weighted (sample)
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DOT	U.S. Department of Transportation
DQO	Data Quality Objective(s)
DTW	Depth to Water (in a monitoring well)
Eh	Oxidation/Reduction Potential, A.K.A (ORP)
EWI	Equal Width Increment
FPC	Flow proportioned composite.
FQAO	Field Quality Assurance Officer
FSP	Field Sampling Plan
FSR	Field Sample Records
HSP	Health and Safety Plan
HWC	Height of Water Column (equal to TWD-DTW)
IDW	Investigation-Derived Waste
LNAPL	Light Non-Aqueous Phase Liquid
NAMS	National Air Monitoring System
NAPL	Non-Aqueous Phase Liquid
NTU	Nephelometric turbidity units
OSHA	Occupational Health and Safety Administration

PCB	Polychlorinated Biphenyls
POTW	Publicly Owned Treatment Works
PPE	Personnel Protective Equipment
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RQAO	Regional Quality Assurance Officer
SAP	Sampling and Analysis Plan
SLAMS	State/Local Air Monitoring Station
SPMS	Special Purpose (Air) Monitoring Stations
SOP	Standard Operating Procedure
TC	Time composite
TCLP	Toxicity Characteristics Leaching Procedure
TCVV	Time-constant varying volume (flow composite collection method)
TSCA	Toxic Substances Control Act
TSD	Treatment, Storage and Disposal (Facility)
TVCV	time-varying constant volume (flow composite collection method)
TWD	Total Well Depth
VOA	Volatile Organic Analysis
VOC	Volatile Organic Compound

Region VIII Field Activities

Revision 0

Date: September 1996

Tables

TABLES FOR
FIELD ACTIVITIES

TABLE 1
REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES FOR AQUEOUS MATRICES
FOR HAZARDOUS WASTE SAMPLING
 (page 1 of 3)

Name	Container ¹	Preservation	Maximum holding time
BACTERIAL TESTS:			
Coliform, total	P, G	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	6 hours
INORGANIC TESTS:			
Chloride	P, G	None required	28 days
Cyanide, total and amenable to chlorination	P, G	Cool, 4°C; if oxidizing agents present add 0.6 g of ascorbic acid per L; adjust pH≥12 with 10N NaOH	14 days
Hydrogen ion (pH)	P, G	None required	Analyze immediately
Nitrate	P, G	Cool, 4°C	48 hours
Sulfate	P, G	Cool, 4°C	28 days
Sulfide	P, G	Cool, 4°C, add zinc acetate	7 days
METALS:			
Chromium VI	P, G	Cool, 4°C	24 hours
Mercury	P, G	HNO ₃ to pH<2	38 days in glass, 13 days in plastic
Metals, except chromium VI and Mercury	P, G	HNO ₃ to pH<2	6 months
ORGANIC TESTS:			
Oil and grease	G	Cool, 4°C ²	28 days
Organic carbon, total (TOC)	P, G	Cool, 4°C ²	28 days
Purgeable Halocarbons	G, Teflon-lined septum	Cool, 4°C ³	14 days
Purgeable aromatic hydrocarbons	G, Teflon-lined septum	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ^{2,3}	14 days

TABLE 1

REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES FOR AQUEOUS MATRICES
FOR HAZARDOUS WASTE SAMPLING
(page 2 of 3)

Name	Container ¹	Preservation	Maximum holding time
ORGANIC TESTS, cont'd:			
Acrolein and acrylonitrile	G, Teflon- lined septum	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ , adjust pH to 4-5	14 days
Phenols	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	7 days until extraction, 40 days after extraction
Benzidines	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	7 days until extraction, 40 days after extraction
Phthalate esters	G, Teflon- lined cap	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitrosamines	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ , store in dark	7 days until extraction, 40 days after extraction
PCBs	G, Teflon- lined cap	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitroaromatics and cyclic ketones	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ , store in dark	7 days until extraction, 40 days after extraction
Polynuclear aromatic hydrocarbons	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ , store in dark	7 days until extraction, 40 days after extraction
Haloethers	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	7 days until extraction, 40 days after extraction
Chlorinated hydrocarbons	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	7 days until extraction, 40 days after extraction
Dioxins and Furans	G, Teflon- lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃	7 days until extraction, 40 days after extraction
Total organic halides (TOX)	G, Teflon- lined cap	Cool, 4°C ²	28 days
Pesticides	G, Teflon- lined cap	Cool, 4°C, pH 5-9	7 days until extraction, 40 days after extraction

TABLE 1

**REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES FOR AQUEOUS MATRICES
FOR HAZARDOUS WASTE SAMPLING**

(page 3 of 3)

Name	Container ¹	Preservation	Maximum holding time
RADIOLOGICAL TESTS: Alpha, beta and radium	P, G	HNO ³ to pH<2	6 months

Source: SW-846, Chapter 2
Revision 1, July 1992
Table 2-21

¹Polyethylene (P), or Glass (G)

²Adjust to pH<2 with H₂SO₄, HCL or solid NaHSO₄

³Free chlorine must be removed prior to addition of HCL by the appropriate addition of Na₂S₂O₃

TABLE 2

**RECOMMENDED SAMPLE CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES
FOR SOILS FOR HAZARDOUS WASTE SAMPLING**

(page 1 of 2)

Analyte Class	Container	Preservation	Maximum holding time
<u>VOLATILE ORGANICS</u>			
Concentrated Waste Samples	8 oz. wide-mouth glass jar with Teflon liner	None	14 days
Liquid Samples			
No Residual Chlorine Present	2 X 40 mL vials with Teflon lined septum caps.	Cool to 4°C ¹	14 days
Residual Chlorine Present	2 X 40 mL vials with Teflon lined septum caps. See preservation requirements at right.	Collect sample in a 4 oz. soil VOA container which has been pre-preserved with 4 drops of 10 % sodium thiosulfate. Gently mix sample and transfer to a 40 mL VOA vial ¹ . Cool to 4°C.	14 days
Acrolein and Acrylonitrile	2 X 40 mL vials with Teflon lined septum caps.	Adjust to pH 4-5, Cool to 4°C	14 days
Soil/Sediments and Sludges	4 oz wide-mouth glass jar with Teflon liner, or wide mouth glass container sealed with aseptum.	Cool to 4°C	14 days

TABLE 2

**RECOMMENDED SAMPLE CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES
FOR SOILS FOR HAZARDOUS WASTE SAMPLING**
(page 2 of 2)

Analyte Class	Container	Preservation	Maximum holding time
<u>SEMIVOLATILE ORGANICS/ORGANOCHLORINE PESTICIDES/PCBs AND HERBICIDES</u>			
Concentrated Waste Samples	8 oz. wide-mouth glass jar with Teflon liner	None	Samples must be extracted within 14 days and extracts analyzed within 40 days following extraction.
Water Samples			
No Residual Chlorine Present	1 gal. or 2.5 gal. amber glass with Teflon liner	Cool to 4°C	Samples must be extracted within 7 days and extracts analyzed within 40 days following extraction.
Residual Chlorine Present	1 gal. or 2.5 gal. amber glass with Teflon liner	Add 3 mL 10% sodium thiosulfate per gallon, Cool, 4°C	Samples must be extracted within 7 days and extracts analyzed within 40 days following extraction.
Soil/Sediments and Sludges	8 oz. wide-mouth glass jar with Teflon liner	Cool to 4°C	Samples must be extracted within 14 days and extracts analyzed within 40 days following extraction.

¹Adjust pH <2 with H₂SO₄, HCL or solid NaHSO₄.

Source: SW-846, Chapter 4
Revision 1, November 1990 - Table 4-1.

TABLE 3

REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIME FOR NON-HAZARDOUS WASTE PROGRAMS

(page 1 of 5)

Parameter No./Name	Container ¹	Preservation ^{2,3}	Maximum holding time ⁴
BACTERIAL TESTS:			
1-4. Coliform, fecal and total	P,G	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	6 hours
5. Fecal streptococci	P,G	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	6 hours
INORGANIC TESTS:			
1. Acidity	P,G	Cool, 4°C	14 days
2. Alkalinity	P,G	Cool, 4°C	14 days
4. Ammonia	P,G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
9. Biochemical oxygen demand	P,G	Cool, 4°C	48 hours
11. Bromide	P,G	None required	28 days
14. Biochemical oxygen demand, carbonaceous.	P,G	Cool, 4°C	48 hours
15. Chemical oxygen demand	P,G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
16. Chloride	P,G	None required	28 days
17. Chlorine, total residual	P,G	None required	Analyze immediately
21. Color	P,G	Cool, 4°C	48 hours
23-24 Cyanide, total and amenable to chlorination	P,G	Cool, 4°C, NaOH to pH>12, 0.6g ascorbic acid ⁵	14 days ⁶
25. Fluoride	P	None required	28 days
27. Hardness	P,G	HNO ₃ to pH<2, H ₂ SO ₄ to pH<2	6 months
28. Hydrogen ion (pH)	P,G	None required	Analyze immediately
31, 43. Kjeldahl and organic nitrogen	P,G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
METALS:⁷			
18. Chromium VI	P,G	Cool, 4°C	24 hours
35. Mercury	P,G	HNO ₃ to pH<2	28 days
3, 5-8, 10, 12, 13, 19, 20, 22, 26, 29, 30, 32-34, 36, 37, 45, 47, 51, 52, 58-60, 62, 63, 70-72, 74, 75. Metals, except chromium VI and mercury.	P,G	HNO ₃ to pH<2	6 months

TABLE 3

**REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIME
FOR NON-HAZARDOUS WASTE PROGRAMS**
(page 2 of 5)

Parameter No./Name	Container ¹	Preservation ^{2,3}	Maximum holding time ⁴
METALS, cont'd:			
38. Nitrate	P,G	Cool, 4°C	48 hours
39. Nitrate-nitrite	P,G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
40. Nitrite	P,G	Cool, 4°C	48 hours
41. Oil and grease	G	Cool, 4°C, HCl or H ₂ SO ₄ to pH<2	28 hours
42. Organic carbon	P,G	Cool, 4°C, HCl or H ₂ SO ₄ to pH<2	28 hours
44. Orthophosphate	P,G	Filter immediately, Cool, 4°C	48 hour
46. Oxygen, Dissolved Probe	G bottle and top	None required	Analyze immediately
47. Winkler	G bottle and top	Fix on site and store in dark	8 hours
48. Phenols	G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
49. Phosphorus (elemental)	G	Cool, 4°C	48 hours
50. Phosphorus, total	P,G	Cool, 4°C, H ₂ SO ₄ to pH<2	28 days
53. Residue, total	P,G	Cool, 4°C	7 days
54. Residue, Filterable	P,G	Cool, 4°C	7 days
55. Residue, Nonfilterable (TSS)	P,G	Cool, 4°C	7 days
56. Residue, Settleable	P,G	Cool, 4°C	48 hours
57. Residue, volatile	P,G	Cool, 4°C	7 days
61. Silica	P	Cool, 4°C	28 days
64. Specific conductance	P,G	Cool, 4°C	28 days
65. Sulfate	P,G	Cool, 4°C	28 days
66. Sulfide	P,G	Cool, 4°C add zinc acetate plus sodium hydroxide to pH>9.	7 days
67. Sulfite	P,G	None required	Analyze immediately
68. Surfactants	P,G	Cool, 4°C	48 hours
69. Temperature	P,G	None required	Analyze in field
73. Turbidity	P,G	Cool, 4°C	48 hours

TABLE 3

REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIME
FOR NON-HAZARDOUS WASTE PROGRAMS
(page 3 of 5)

Parameter No./Name	Container ¹	Preservation ^{2,3}	Maximum holding time ⁴
ORGANIC TESTS⁸			
13, 18-20, 22, 24-28, 34-37, 39-43, 45-47, 56, 66, 88, 92-95, 97. Purgeable Halocarbons	G, Teflon-lined septum	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	14 days
6, 57, 90, Purgeable aromatic hydrocarbons	G, Teflon-lined septum	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵ HCl to pH2 ⁹	14 days
3, 4, Acrolein and acrylonitrile	G, Teflon-lined septum	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵ Adjust pH to 4-5 ¹⁰	14 days
23, 30, 44, 49, 53, 67, 70, 71, 83, 85, 96 Phenols ¹¹ .	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	7 days until extraction; 40 days after extraction
7, 38, Benzidines ¹¹	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	7 days until extraction ¹³
14, 17, 48, 50-52. Phthalate esters ¹¹	G, Teflon-lined cap	Cool, 4°C	7 days until extraction; 40 days after extraction.
72-74. Nitrosamines ^{11,14}	G, Teflon-lined cap	Cool, 4°C, store in dark, 0.008% Na ₂ S ₂ O ₃ ⁵	7 days til extr., 40 days after
76-82, PCBs ¹¹ acrylonitrile	G, Teflon-	Cool, 4°C	7 days til extr., 40 days after
54, 55, 65, 69. Nitroaromatics and isophorone ¹¹	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵ store in dark.	7 days til extr., 40 days after
1, 2, 5, 8-12, 32, 33, 58, 59, 64, 68, 84, 86. Polynuclear aromatic hydrocarbons ¹¹	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵ store in dark.	7 days til extr., 40 days after
15, 16, 21, 31, 75. Haloethers ¹¹	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	7 days til extr., 40 days after
29, 35-37, 60-63, 91. Chlorinated hydrocarbons ¹¹	G, Teflon-lined cap	Cool, 4°C	7 days til extr., 40 days after
87. TCDD ¹¹	G, Teflon-lined cap	Cool, 4°C, 0.008% Na ₂ S ₂ O ₃ ⁵	7 days til extr., 40 days after

TABLE 3

REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIME
FOR NON-HAZARDOUS WASTE PROGRAMS
(page 4 of 5)

Parameter No./Name	Container ¹	Preservation ^{2,3}	Maximum holding time ⁴
PESTICIDES TESTS: 1-70. Pesticides ¹¹	G, Teflon-lined cap	Cool, 4°C, pH 5-9 ¹⁵	7 days til extr., 40 days after
RADIOLOGICAL TESTS: 1-5. Alpha, beta and radium	P, G	HNO ₃ to pH<2	6 months

TABLE 3 NOTES:

¹Polyethylene (P) or Glass (G)

²Sample preservation should be performed immediately upon sample collection. For composite chemical samples each aliquot should be preserved at the time of collection. When use of an automated sampler makes it impossible to preserve each aliquot, then chemical samples may be preserved by maintaining at 4°C until compositing and sample splitting is completed.

³When any sample is to be shipped by common carrier or sent through the United States Mails, it must comply with the Department of Transportation Hazardous Materials Regulations (49 CFR part 172). The person offering such material for transportation is responsible for ensuring such compliance. For the preservation requirements of Table II, the Office of Hazardous Materials, Materials Transportation Bureau, Department of Transportation has determined that the Hazardous Materials Regulations do not apply to the following materials: Hydrochloric acid (HCl) in water solutions at concentrations of 0.04% by weight or less (pH about 1.96 or greater); Nitric acid (HNO₃) in water solutions at concentrations of 0.15% by weight or less (pH about 1.62 or greater); Sulfuric acid (H₂SO₄) in water solutions at concentrations of 0.35% by weight or less (pH about 1.15 or greater); and Sodium hydroxide (NaOH) in water solutions at concentrations of 0.080% by weight or less (pH about 12.30 or less).

⁴Samples should be analyzed as soon as possible after collection. The times listed are the maximum times that samples may be held before analysis and still be considered valid. Samples may be held for longer periods only if the permittee, or monitoring laboratory, has data on file to show that the specific types of samples under study are stable for the longer time, and has received a variance from the Regional Administrator under § 136.3(e). Some samples may not be stable for the maximum time period given in the table. A permittee, or monitoring laboratory, is obligated to hold the sample for a shorter time if knowledge exists to show that this is necessary to maintain sample stability. See § 136.3(e) for details.

TABLE 3.

**REQUIRED CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIME
FOR NON-HAZARDOUS WASTE PROGRAMS**

(page 5 of 5)

⁸Should only be used in the presence of residual chlorine.

⁹Maximum holding time is 24 hours when sulfide is present. Optionally all samples may be tested with lead acetate paper before pH adjustment in order to determine if sulfide is present. If sulfide is present, it can be removed by the addition of cadmium nitrate powder until a negative spot test is obtained. The sample is filtered and then NaOH is added to pH 12.

⁷Samples should be filtered immediately on-site before adding preservative for dissolved metals.

⁶Guidance applies to samples to be analyzed by GC, LC, or GC/MS for specific compounds.

⁵Sample receiving no pH adjustment must be analyzed within seven days of sampling.

¹⁰The pH adjustment is not required if acrolein will not be measured. Samples for acrolein receiving no pH adjustment must be analyzed within 3 days of sampling.

¹¹When the extractable analytes of concern fall within a single chemical category, the specified preservative and maximum holding times should be observed for optimum safeguard of sample integrity. When the analytes of concern fall within two or more chemical categories, the sample may be preserved by cooling to 4°C, reducing residual chlorine with 0.008% sodium thiosulfate, storing in the dark, and adjusting the pH to 6-9; samples preserved in this manner may be held for seven days before extraction and for forty days after extraction. Exceptions to this optional preservation and holding time procedure are noted in footnote 5 (re the requirement for thiosulfate reduction of residual chlorine), and footnotes 12, and 13 (re the analysis of benzidine).

¹²If 1,2-diphenylhydrazine is likely to be present, adjust the pH of the sample to 4.0±0.2 to prevent rearrangement to benzidine.

¹³Extracts may be stored up to 7 days before analysis if storage is conducted under an inert (oxidant-free) atmosphere.

¹⁴For the analysis of diphenylnitrosamine, add 0.008% Na₂S₂O₃ and adjust pH to 7-10 with NaOH within 24 hours of sampling.

¹⁵The pH adjustment may be performed upon receipt at the laboratory and may be omitted if the samples are extracted within 72 hours of collection. For the analysis of aldrin, add 0.008% Na₂S₂O₃.

Source: 40 CFR 136.3(b) Table II

TABLE 4
TOXICITY CHARACTERISTIC LEACHING PROCEDURE (TCLP)
Sample Maximum Holding Times (Days)

	From Field Collection to TCLP Extraction	From TCLP Extraction to Preparative Extraction	From Preparative Extraction to Determinative Analysis	Total Time
Volatiles	14	NA	14	28
Semivolatiles	14	7	40	61
Mercury	28	NA	28	56
Metals	180	NA	180	360

TABLE 5
GUIDELINES FOR MINIMUM QA/QC SAMPLES¹
FOR FIELD SAMPLING PROGRAMS

Medium	Replicates	Field Blanks ²	Trip Blanks ⁴	Rinseate Blanks ³	Background Samples
Aqueous	one in twenty	one per sampling area	one per shipping container with VOC samples	one per 20 decontamination procedures	minimum of one per sampling event per medium
Soil, Sediment	one in twenty	one per sampling area	one per shipping container with VOC samples	one per 20 decontamination procedures	minimum of one per sampling event per medium
Air	one in twenty		one per shipping container with VOC samples	one per 20 decontamination procedures	minimum of one per sampling event per medium
Source Material	one in twenty	one per sampling area		one per 20 decontamination procedures	

NOTES:

- 1) QA/QC requirements on a site-specific basis may dictate a more stringent frequency. Laboratory blanks and spikes are method-specific and are not included in this table. However, as a minimum, 10% of laboratory analyses must be QC samples.
- 2) Field blanks are required when background contamination of the breathing zone is detected. One should be collected from each different industrial or functional area sampled during the most active time of day.
- 3) Replicate and rinseate samples are collected at the minimum rate of 1 per 20 samples/decon. procedures. If fewer than 20 samples are collected, one replicate and one rinseate sample must be collected.
- 4) Trip blanks are prepared in the laboratory or at another off-site location from distilled or deionized water. They are never prepared on-site, or from soils or other solid material.

TABLE 6
STANDARD PRESERVATIVES LISTED IN THE HAZARDOUS MATERIALS
TABLE (49 CFR § 172.101) USED BY EPA FOR PRESERVATION OF WATER,
EFFLUENT, BIOLOGICAL SEDIMENT AND SLUDGE SAMPLES

Preservative	Sample Type/Parameter	Recommended pH	Quantity of Preservative Added	Weight % of Preservation	Hazard Class	DOT Label	Packaging Exceptions	Specific Requirements (49 CFR)
HCl	Organic Carbon	< 2 (=1.9)	2 ml of 1:1	0.04	Corrosive material	Corrosive	173.244	173.263
HgCl ₂	Nitrogen Species	N.A.	40 mg	0.004	Poison B	Poison	173.364	173.372
HNO ₃	Metals, Hardness*	< 2 (=1.6)	3ml of 1:1	0.15	Oxidizer; corrosive material	Oxidizer and corrosive ; & poison corrosive	None	173.268
H ₂ SO ₄	Nitrogen species, COD, Oil & Grease P (hydrolyzable), Organic Carbon	< 2 (=1.15)	2 ml of 36N	0.35	Corrosive material	Corrosive	173.244 173.248	173.272
NaOH	Cyanide	> 12 (=12.3)	2 ml of 10N	0.080	Corrosive material	Corrosive	173.244	173.245(b)
H ₃ PO ₄	Phenolics	< 4	Sufficient to yield desired pH	Varies	Corrosive material	Corrosive	173.244	173.245
Freezing 0°C (Dry Ice)	Biological - Fish & shellfish tissue**	N.A.	N.A.	N.A.	None	None	None	173.615

* If sample must be shipped by passenger aircraft or railcar, the sample may be initially preserved by icing and immediately shipping it to the laboratory. Upon receipt in the laboratory, the sample must be acidified with conc. HNO₃ to pH 2. At time of analysis, sample container should be thoroughly rinsed with 1:1 HNO₃; washings should be added to sample.

** Dry ice is classified as an ORN-A hazard by DOT. There are no labeling requirements for samples preserved with dry ice, but samples must be packaged in accordance with the requirements of 49 CFR 173.615 and advance arrangements must be made between the shipper and the air carrier.

EXHIBIT A

EXAMPLE OUTLINE OF A SAMPLING AND ANALYSIS PLAN

(page 1 of 2)

I. TITLE PAGE

- A. Name of Project
- B. Name of Lead Group (State, County, Contractor, etc.)
- C. Signature Lines for approval
 - 1. Project Officer
 - 2. Project Officer's First Line Supervisor
 - 3. Others if wanted (e.g., Section, Branch Chiefs)

II. BACKGROUND

- A. Site Location
- B. What has happened (spills, ponds - covered, constructed, etc.)
- C. What types of samples have been taken and summary of data.
Consider the hazard and include (i.e., 0-10 ppm, 10-150,000 ppm, >150,000 ppm).

III. DATA QUALITY OBJECTIVES

- A. What needs to be proved?
- B. How can we prove it with resources available?
- C. Consider health problems for humans, wildlife, and livestock

IV. SAMPLES AND PARAMETERS (volatile organics, semivolatiles, metals, etc.)

- A. Locations (surface, ponds, streams, air, tanks, barrels, etc.)
- B. Types
 - 1. Soil
 - 2. Sediment
 - 3. Water
 - 4. Animal tissue
 - 5. Plant tissue
 - 6. Bioassay
- C. Preservation, holding times, containers
- D. How will samples be collected?
- E. Decontamination of sampling equipment (if needed)
- F. Disposal of purged waters (groundwater sampling)
- G. Disposal of decontamination rinsates

V. FIELD QUALITY CONTROL (QC) SAMPLES

- A. Background (Least Affected/natural Area)
- B. Duplicates (surface water or other homogeneous matrix)
- C. Field blanks

EXHIBIT A

EXAMPLE OUTLINE OF A SAMPLING AND ANALYSIS PLAN

(page 2 of 2)

- D. Equipment/decontamination blanks
(only if equipment needs to be decontaminated)
- E. Trip blanks (VOAs only)
- F. Other background or control samples

VI. CALIBRATION AND MAINTENANCE OF EQUIPMENT

- A. Calibration Methods
- B. Documentation
- C. Equipment Repair

VII. ANALYTICAL METHODS AND QUALITY CONTROL SAMPLES

- A. 40 CFR 136
- B. SW-846
- C. Other approved methods
(consider the detection levels you need for data quality objectives)

VIII. LABORATORY

- A. Name and location
- B. How shipment will be made

IX. CHAIN-OF-CUSTODY

- A. Tags
- B. Custody Sheets - Discuss documentation
(who signs, what information is included on both forms)
- C. Shipping containers - How will these be sealed?

X. DATA VALIDATION

- A. Check for QC contamination
- B. Check precision of field samples
- C. Check precision and accuracy of laboratory analysis
- D. Overall data usability

XI. HEALTH AND SAFETY

- A. Site safety plan
 - 1. Safety equipment and clothing
 - 2. Local and emergency facilities

XII. REPORT GENERATION

- A. Who will generate and in what time

EXHIBIT B
ELEMENTS REQUIRED IN A
QUALITY ASSURANCE PROJECT PLAN

- A1 Title and Approval Sheet
- A2 Table of Contents
- A4 Project/Task Organization
- A5 Problem Definition/Background
- A6 Project/Task Description
- A7 Data Quality Objectives for Measurement Data
- B1 Sampling Process Design (Experimental Design)
- B2 Sampling Methods Requirements
- B3 Sample Handling and Custody Requirements
- B4 Analytical Methods Requirements
- B5 Quality Control Requirements
- B7 Instrument Calibration and Frequency
- C1 Assessments and Response Actions
- D1 Data Review, Validation and Verification Requirements
- D2 Validation and Verification Methods
- D3 Reconciliation with DQOs

EXHIBIT C
EPA SAMPLE TAG

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REGION VIII
999 18TH STREET
Denver, Colorado 80202-2405



R8EPA-014A (7-88)

U.S.GPO: 1997-575-022


Project Code	Station No.	Month/Day/Year	Time	Designate:		Preservative: Yes <input type="checkbox"/> No <input type="checkbox"/>																																						
				Comp.	Grab																																							
Station Location				ANALYSES																																								
				<table border="1"> <tr> <td>BOD</td> <td>Anions</td> <td></td> </tr> <tr> <td>Solids</td> <td>(TSS) (TDS) (SS)</td> <td></td> </tr> <tr> <td colspan="2">COD, TOC, Nutrients</td> <td></td> </tr> <tr> <td colspan="2">Phenolics</td> <td></td> </tr> <tr> <td colspan="2">Mercury</td> <td></td> </tr> <tr> <td colspan="2">Metals</td> <td></td> </tr> <tr> <td colspan="2">Cyanide</td> <td></td> </tr> <tr> <td colspan="2">Oil and Grease</td> <td></td> </tr> <tr> <td colspan="2">Organics GC/MS</td> <td></td> </tr> <tr> <td colspan="2">Priority Pollutants</td> <td></td> </tr> <tr> <td colspan="2">Volatile Organics</td> <td></td> </tr> <tr> <td colspan="2">Pesticides</td> <td></td> </tr> <tr> <td colspan="2">Mutagenicity</td> <td></td> </tr> <tr> <td colspan="2">Bacteriology</td> <td></td> </tr> </table>			BOD	Anions		Solids	(TSS) (TDS) (SS)		COD, TOC, Nutrients			Phenolics			Mercury			Metals			Cyanide			Oil and Grease			Organics GC/MS			Priority Pollutants			Volatile Organics			Pesticides			Mutagenicity	
BOD	Anions																																											
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Mutagenicity																																												
Bacteriology																																												
Remarks:																																												
Tag No.				Lab Sample No.																																								

EXHIBIT D
CHAIN-OF-CUSTODY RECORD

[illegible]

EXHIBIT B
EPA CUSTODY SEAL

EPA FORM
7500-2 (R7-75)

		<p style="text-align: center;">UNITED STATES ENVIRONMENTAL PROTECTION AGENCY OFFICIAL SAMPLE SEAL</p>
<p>SAMPLE NO.</p>	<p>DATE</p>	<p style="text-align: center;">SEAL BROKEN BY</p>
<p>SIGNATURE</p>		<p>DATE</p>
<p>PRINT NAME AND TITLE (Inspector, Analyst or Technician)</p>		

RECEIPT FOR SAMPLES

Colorado. Montana.
North Dakota. South Dakota
Utah. Wyoming

G EPA

(Date)

(Signature)

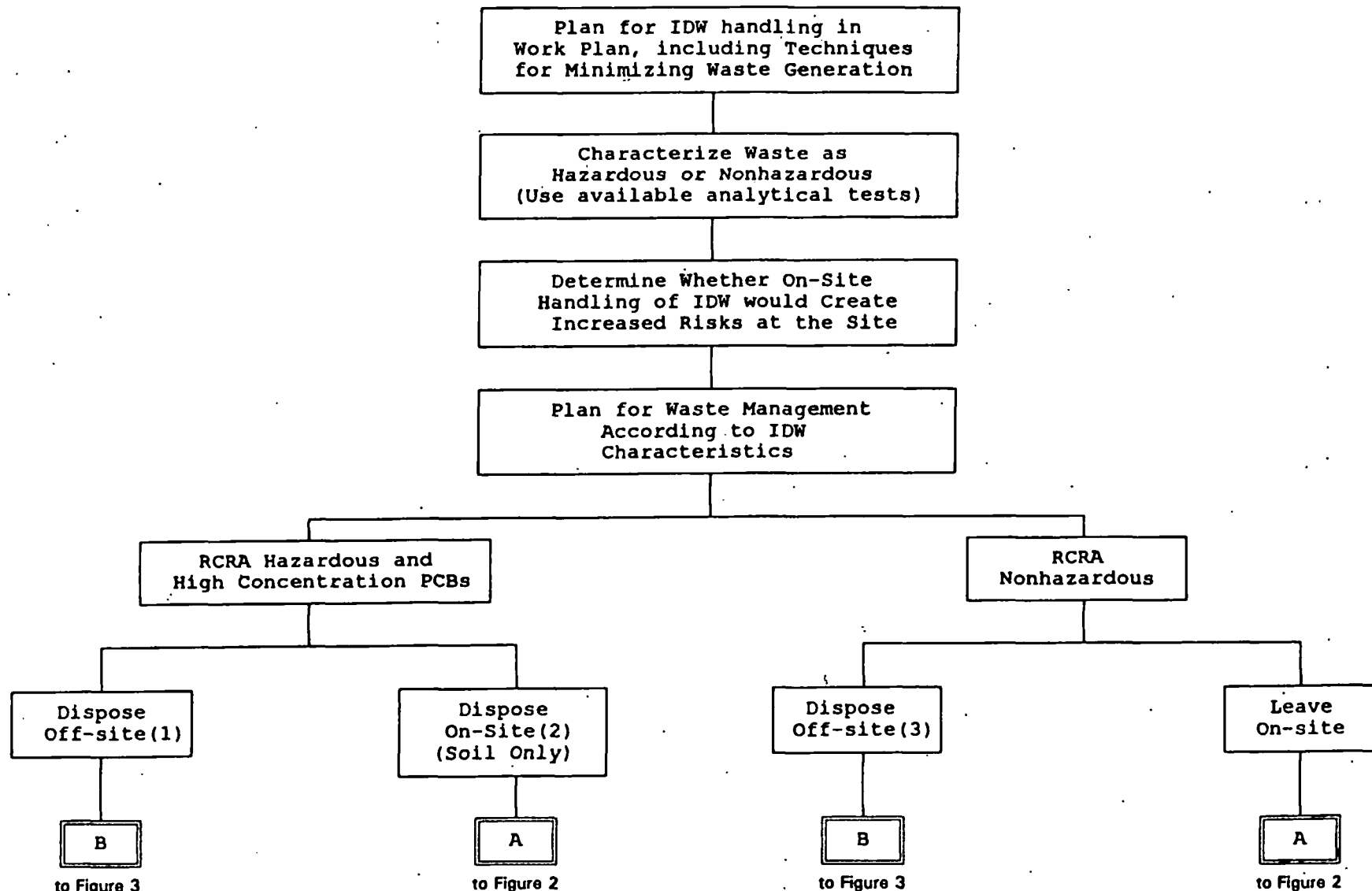
[illegible]

(Date)

DISTRIBUTION: One copy to Facility Representative
One copy for Inspector's Records
Original to Regional Office .

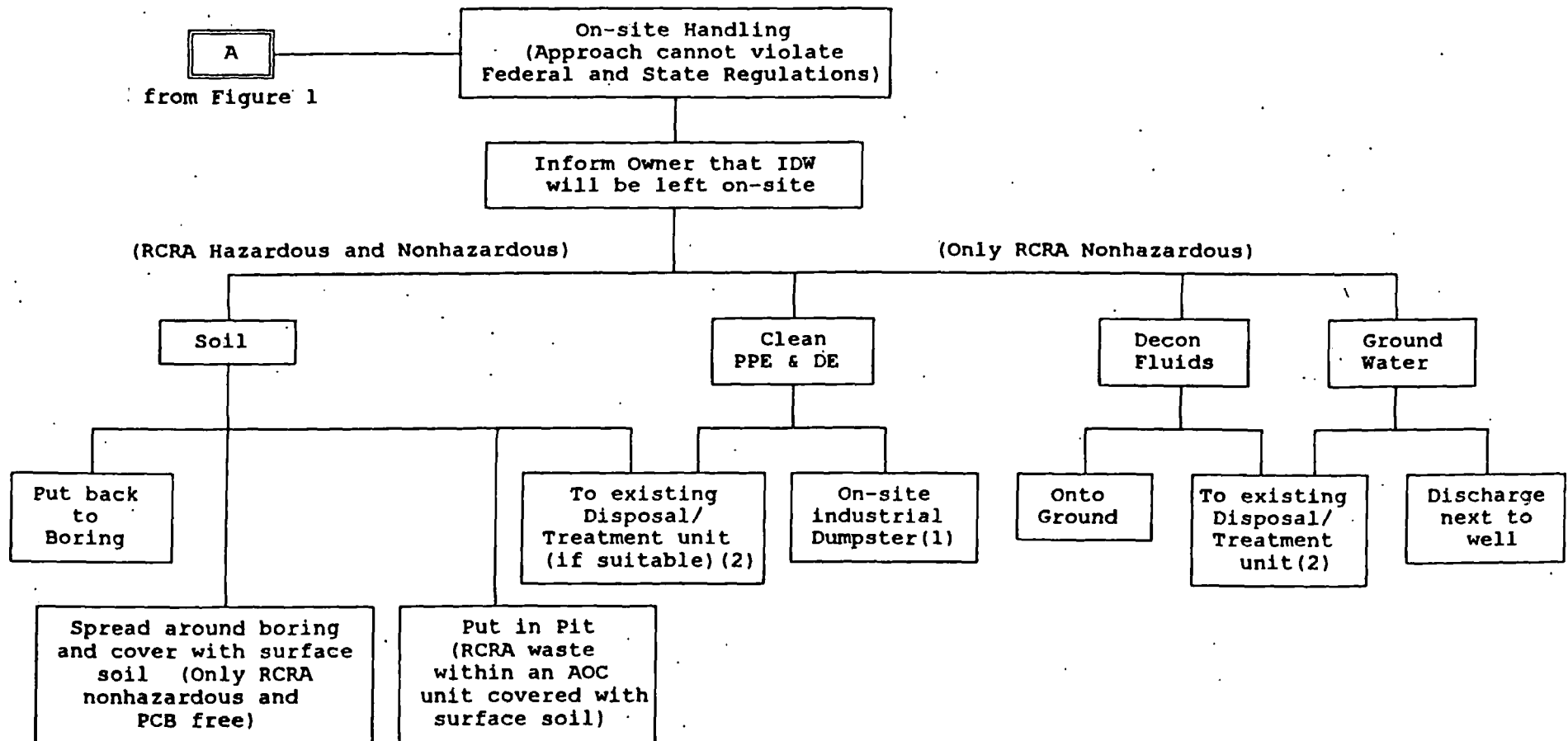
EXHIBIT G :
DECISION TREE FOR MANAGEMENT OF
INVESTIGATION-DERIVED WASTE
(Figure 1 of 3)

Region VIII Field Activities
Revision 0
Date: September 1996
Exhibits



- (1) Soil cuttings, ground water, and decontamination fluids creating increased hazards at the site should be disposed off-site. Before and after the Site Investigation, determine anticipated waste quantity and applicable regulations for waste generators.
- (2) If not prohibited by other legally enforceable requirements such as state ARARs.
- (3) Justified only in rare circumstances when a RCRA nonhazardous waste is a state hazardous waste, and the state's legally enforceable requirements call for waste removal; or if leaving the waste on-site would significantly affect human health and the environment.

EXHIBIT G
DECISION TREE FOR MANAGEMENT OF
INVESTIGATION-DERIVED WASTE
(Figure 2 of 3)

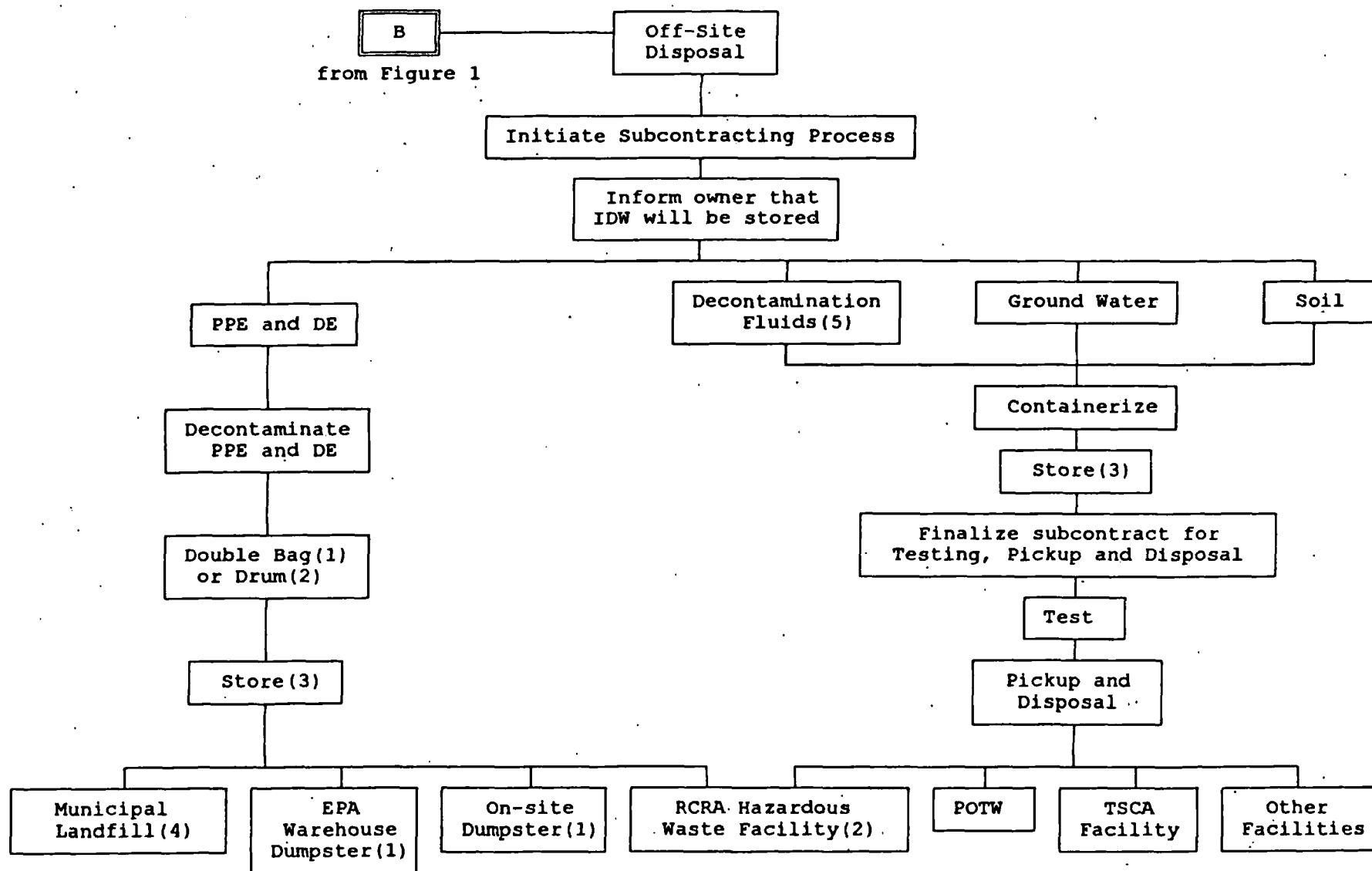


(1) Clean PPE and DE may also go to the nearest landfill or to an EPA warehouse dumpster.

(2) If the receiving unit meets the off-site policy acceptability criteria.

EXHIBIT G
DECISION TREE FOR MANAGEMENT OF
INVESTIGATION-DERIVED WASTE
 (Figure 3 of 3)

Region VIII Field Activities
 Revision 0
 Date: September 1996
 Exhibits



(1) Only RCRA nonhazardous waste.

(2) Only RCRA hazardous waste generated in quantities greater than 100 kg/month when sent off-site.

(3) In accordance with accumulation requirements for RCRA hazardous wastes.

(4) Only if the conditionally exempt small quantity generator exception applies.

(5) If the conditionally exempt small quantity generator exception applies, off-site disposal of decon fluids may not require subcontracting.



November 18, 1998

**Ft. Peck Ground-water Contamination
Summary of the Status of Oil and Gas Well
in Southern Portion of East Poplar Field**

by

**Paul Stephen Osborne
National Ground Water Expert
Region VIII**

As requested, I have been reviewing the well files obtained from state files and some related correspondence and well file information from the BLM. This information was mainly collected by Jim Boyter but contains the data sent to us by Debbie Madison, Ft Peck Tribes. So far I do not see any identifiable "suspect wells except for the Judith River dry hole in Section 23. This is outside of the high TDS zone surveyed by the USGS study. In reviewing the correspondence from the BLM, however, there is a reference to a salt water line running through section 27 which was intended to carry hot Madison brine from the Mesa Biere Site to Poplar for heating purposes. This line is very close to the wells owned by the Trottier family (NW NW NW Sect. 27, T28N, R51E) which became contaminated in 1988. The BLM inspector, Patrick Roddy, who accompanied Debbie Madison to the site indicated that the inspection team assumed that the line had no water in it. There is nothing to indicate that this was followed up on with the operator. I am surprised that this potential source was not mentioned to us by Debbie Madison, but she may have eliminated it as a source and assumed that we had the relevant information. I would recommend some follow up to clearly eliminate this as a source.

The following bullets summarizes the information in the well files I have collected to date on oil and gas holes drilled in the vicinity of the ground-water problem:

1. Murphy EPU 100 SW SE Section 11, T28N, R51E-drilled to 5925 (Madison target), 9 5/8" surface casing set to 1036 and cemented with 400 sacks with a 50 sack return to the surface, 5 1/2" longstring casing set to 5925 and cemented with 300 sacks. Well was used as an injection well. There is a record of at least one casing repair at 3937 ft in 1963.

2. Murphy EPU 68 SW SE Section 11, T28N, R51E-drilled to 5960 (Madison A target), 9 5/8" surface casing set to 1017 with 400 sacks circulated to the surface, 5 1/2" longstring casing set to 5960 with 300 sacks (perforated from 5614-5619) put on TA status in 1969. Was still shut-in as of Feb. 18, 1993 because well was not economic to produce.

3. Murphy EPU 24 SW SW Section 12, T28N, R51E- drilled in 1953 to 5926 (Madison A target), 9 5/8" surface casing set to 987 with 400 sacks circulated to the surface, 5 1/2" longstring set to 5938 and cemented with 250 sacks (perforated from 5920 to 5605). No record of subsequent work. Need update of workovers, etc.

4. Murphy EPU 61 SE NE Section 12, T28N, R51W-drilled in 1955 to 5943. 9 5/8" surface casing set to 1057 and cemented with 700 sacks (why so much not explained, but circulation lost while cementing (top at 200), added 100 sacks with 1" tremmie pipe to surface, 5 1/2 " longstring set to 5933 and cemented with 300 sacks (pipe froze while cementing (perforated 5606 to 5617). Plugged in 1960 by setting plug from 5632 to 5380, pulled 5300 feet of 5 1/2" casing, set plug at base of surface casing.

5. Murphy EPU 74 SE SW Section 13, T28N, R51E-drilled in 1956 to 5930. 9 5/8" surface casing set to 1038 and cemented to surface with 400 sacks (50 sacks clean cement to surface), 5 1/2" longstring set to 5934 and cemented with 300 sacks (perforated 5597 to 5604). Plugged in 1976 by setting a bridge plug at 4710 with 10 feet of cement on top, casing cut at approx. 3754 and 50 foot plug set on casing stub, a 100 foot plug was set at top of Dakota at 3213, a 100 foot plug was set at base of surface casing (1/2 in and 1/2 out), and a 10 foot plug was set at the surface.

6. Murphy EPU 22 SW SW Section 14, T28N, R51E-drilled in 1953 to 5940. 9 5/8 surface casing set to 1004 with 400 sacks circulated to the surface, 5 1/2" longstring set to 5929 with 250 sacks (perforated 5908 to 5918). No other info in file on present status.

7. Murphy EPU 32 SW NE Section 15. T28N, R51E-drilled in 1954 to 5821. 9 5/8" surface casing set to 992' with 390 sacks (may not have come to surface), 5 1/2" longstring set to 5819' with 300 sacks of cement (perforated 5497 to 5666). Well was uneconomic in 1973, but was still shut-in 1995.

8. Juniper 1-21 NW SE Section 21. T28N, R51E-drilled in 1980 to 5966. 9 5/8 surface casing set to 1409 (13 3/4" hole) with 1025 sacks circulated to the surface, 5 1/2" longstring set to 5966 with 150 sacks (perforated 5902 to 5918). Well plugged in 1981 by setting cast iron bridge plug at 5700 with 2 sacks on top and setting a 10 sack plug at the top of the 5 1/2" casing.

9. Murphy EPU 72 (allotted 1-37) SW SE Section 22, T28N, R51E-drilled in 1956 to 5899' (dry hole). 9 5/8 surface casing set to 1060 with 400 sacks circulated to the surface. No longstring set, but 5 plugs set in open hole from 5850 to 4910 (Amsden Formation). A 30 sack plug was set

in the surface casing from 830 to 900 and an 8 sack plug was set on top. This plugging did not isolate some major water zones such as the Dakota or the Eagle.

10. TXO Buckles "SWD" #1 SE NW Section 22, T28N, R51E-drilled in 1981 to 950' (Judith River injector). 7" casing set to 950' in 8 3/4" hole and cemented to the surface with 1310 sacks of cement (bond log was not adequate). Well plugged in 1984 by placing 50 sacks over the perforations, 35 sacks at 685' and 30 sacks at the surface

11. TXO Buckles A-1 SE NW Section 22, T28N, R51E-drilled in 1981 to 5934'. 8 5/8 casing set to 1220' with 1150 sacks of cement circulated to the surface, 5 1/2" casing set to 5933' and cemented with 560 sacks of cement (perforations 5796 to 5800). Well plugged in 1984 by setting plug at perforations, 35 sacks at 5670, 55 sacks at 1300 across casing stub at 1250, 50 sacks at 800 feet and 15 sacks at the surface.

12. Mesa Biere #1-22 NW SW Section 22, T28N, R51E-drilled in 1970 to 5845'. 8 5/8 surface casing set to 741' (does not cover all of Judith River) with 465 sacks, 5 1/2" longstring set to 5845' with 675 sacks of cement. Well plugged in 1984 with 50 sacks over perforations (Top of Cement at 5760), perforated tubing at 5750 and placed 30 sacks outside tubing from 5435 to 5750, perforated tubing from 993 to 996 and pumped 50 sacks down tubing, pumped 85 sacks down 5 1/2" production casing. This well seems to have been a problem plugging as tubing was not pulled.

13. Mesa Biere # 1-22 SWD Judith River Injector SW NW SW Section 22, T28N, R51E-drilled in 1970 to 989'. 8 5/8 casing set to 988' with 500 sacks circulated to the surface and 5 1/2" casing to 749 feet with 25 sacks to surface (perforations 796 to 834'). Plugged in 1984 by squeezing perforations and pumping cement to the surface. A relief well was drilled during the plugging of the two mesa wells, at this site and 5 1/2" casing was set to top of Judith River and cemented to the surface. The purpose of the relief well is very unclear to me, but it was suggested that it was related to the plugging of the Judith River injector. This needs to be verified. A history of the plugging and any problems is needed from the company.

14. Murphy well 3-G NE SW SW Section 23, T28N, R51E-drilled in 1953 to the Judith River as a gas Exploration hole to a depth of 854 feet. Dry hole, surface casing set to 60 feet with 20 sacks. This well was plugged on 12-10-52 by placing 10 sacks at the base of surface casing. This leaves the Judith River able to flow up into surface formations.

15. Murphy Well EPU 26 SW NE Section 23. T28N, R51E-drilled in 1953 to 5943". 9 5/8" surface casing set to 1014' with 400 sacks cemented to the surface and 5 1/2" longstring was set to 5940' with 250 sacks (perforations 5899 to 5909). Well Plugged in 1976 by setting bridge plug at 4700' with 10 sacks. The casing was cut at 2009' with a 50 sack plug over the stub, a 100' plug at the bottom of the 9 5/8 casing (50' inside and outside), and a 10' plug at the surface.

16. Murphy well EPU 55 NW SW Section 23. T28N, R51E-drilled in 1955 to 5937". 9 5/8" surface casing set to 1058' with 400 sacks cemented to the surface and 5 1/2" longstring was set to 5932' with 300 sacks (perforations 5917 to 5927). Need information on present status and workovers.

17. Murphy well EPU 63 SW NE Section 27. T28N, R51E-drilled in 1956 to 5943". 10 3/4" surface casing set to 1049' with 700 sacks cemented to the surface and 5 1/2" longstring was set to 5945' with 350 sacks (perforations 5231 to 5243 also lower zones to 5827). Plugged in 1962 by plugging perfs., cut casing at 3964 and set 25 sack plug on stub, set 25 sack plug at base of surface casing and set 10 sack plug at surface.

18. Amarco 1-27 NW NW Section 27. T28N, R51E-drilled in 1973 to 5943". 13 3/8" surface casing set to 134' with 210 sacks cemented to the surface and 8 5/8" longstring was set to 1002" with 400 sacks. This was a dry hole with 30 sack plugs set at 5730', 5250', 4825', 3600' and 2420 feet. A 10 sack plug was set at the surface. Did not place a plug at the base of the surface casing. The top of the Greenhorn is about 2370'. The plugs will isolate important water zones.

I have the following suggested tasks for looking at the contamination problems in the East Poplar Oil Field:

1. Locate all buried Salt water lines in the southern portion of the field and summarize their operational history, including present status. Prepare a map showing locations. Specific attention should be given to sections 21, 22, 23, 26, 27, and 28, T28N, R51W. A salt water pipeline was reported to run close to the Trottier residence in section 27 where wells have been contaminated. The line is reported to run due south from the Biere site in section 22.
2. Prepare a well summary, which includes location, depth, completion diagram (with estimated cement tops and assumptions for calculations), well drilling and completion report, workover history, summary of present status, and plugging report if applicable, for all wells in Sections 14, 21, 22, 23, 26, 27 and 28.
3. I also strongly recommend that the company conducting this survey be required to prepare a well summary for sections 10 and 11, T28N, R51W containing the same information as required by item 2 above. These sections are contaminated and wells were completed per historical practice in the field. This information will enable EPA to determine the need for further studies.
4. Conduct an EM survey on 100' centers of the area comprising of the southern half of sections 21, 22, and 23, T28N, R51W and the northern half of sections 27 and 28, T28N, R51W. If a potential source anomaly is detected by the survey a 2nd round of measurements using a smaller spacing on 25 to 50 foot centers should be conducted to better delineate the potential problem.

Items 1-3 should be relatively inexpensive to carry out. This will require research time in operator or State files. I would estimate one to 3 man weeks of time depending on the accessibility of the well files and other relevant information. It should be emphasized that although this information is essential for any follow up, the well file data will not answer all of our questions relating to the actual source(s). The well files will enable EPA to be more specific action once a source(s) is more closely pinpointed.

The crux of isolating the actual wells or other sources which are causing the contamination is to carry out further field studies, principally the study outlined in Item 4. The geophysics will be costly because of the close grid spacing needed to define the problem and the size of the area of study which is outlined in green on the attached Xerox copy of the USGS study map. The cost will depend on the number of stations but I would estimate \$75,000 to 100,000 as a crude guesstimate to cover the entire affected area as a means of identifying all potential sources. If a phased approach proves necessary to split up costs, I would suggest running an initial survey of the lower 2/3s of the east half of section 21, the lower 2/3s of the west half of section 22, the NE 1/4 of section 28, the NW 1/4 of section 27, and the western half of the SW 1/4 of section 23. This might pull the cost down to slightly more than \$50,000. I would suggest running this proposed study size by someone who does geophysics and asking them to provide some firmer real numbers.

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CASE HISTORY OF THE EAST POPLAR FIELD ROOSEVELT COUNTY, MONTANA

J. B. Powell, Jr.

XEROX KEEP

ABSTRACT

The discovery well for the East Poplar field was completed in March 1952. As of December 1, 1954, there were 53 producing oil wells in the field which had proven approximately 15,000 acres to be productive.

The field is located on a large, northwest-southeast-trending anticline. Production is obtained from limestone beds in the Charles formation of Mississippian age. The accumulation is partially controlled by porosity variations. During the first eleven months of 1954, more than one out of every five barrels of oil produced in Montana came from the East Poplar field.

INTRODUCTION

The East Poplar field is located 8 miles northeast of the town of Poplar in Roosevelt County of northeastern Montana. The major portion of the field is operated under a Federal Unit Agreement by Murphy Corporation on behalf of The Carter Oil Company, Phillips Petroleum Company, Placid Oil Company, W. C. and Theodosia Nolan, C. F. Lundgren, and Murphy Corporation. Other operators in the field are Empire State Oil Company, C. C. Thomas, and M. R. Wagner.

Since completion of the discovery well in March 1952, development has been carried out to the extent that during the first eleven months of 1954, more than one out of every five barrels of oil produced in Montana came from the East Poplar field.

LOCATION

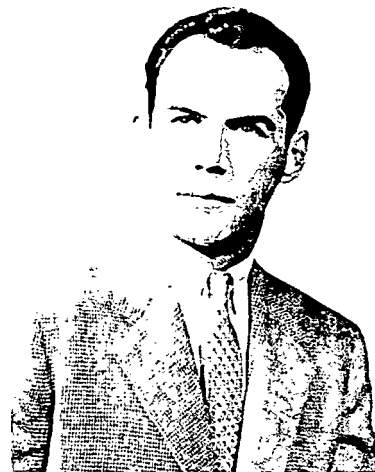
Geologically, the East Poplar field is located on the west flank of the Williston Basin, approximately midway between the Nesson anticline and Bowdoin Dome, and about 60 miles north of the northernmost expression of the Cedar Creek anticline as such (See Figure 1). More specifically, the field is situated on the northeast flank of a fairly prominent southeasterly plunging regional nose referred to in the literature as the Poplar anticline.

Physiographically, the field is located in the Missouri Plateau section of the Great Plains province, approximately 6 miles north of the Missouri River flood plain. Surface elevations within the field limits vary between 2000 and 2300 feet above sea level. The lowest elevations occur on the bottom lands of the Poplar River which crosses the field in a general south-southwest direction.

DISCOVERY AND HISTORY OF DEVELOPMENT

The discovery well for the field, East Poplar Unit Well No. 1, was located in the SW $\frac{1}{4}$ NE $\frac{1}{4}$ Section 2, Township 28 North, Range 51 East, on

¹Geologist, Murphy Corporation. The writer wishes to publicly thank Gordon Kirby and Stratton H. Bull, Murphy Corporation, for their constructive criticism of this paper, and Gabriel Perjessy for the drafting of illustrations herein.



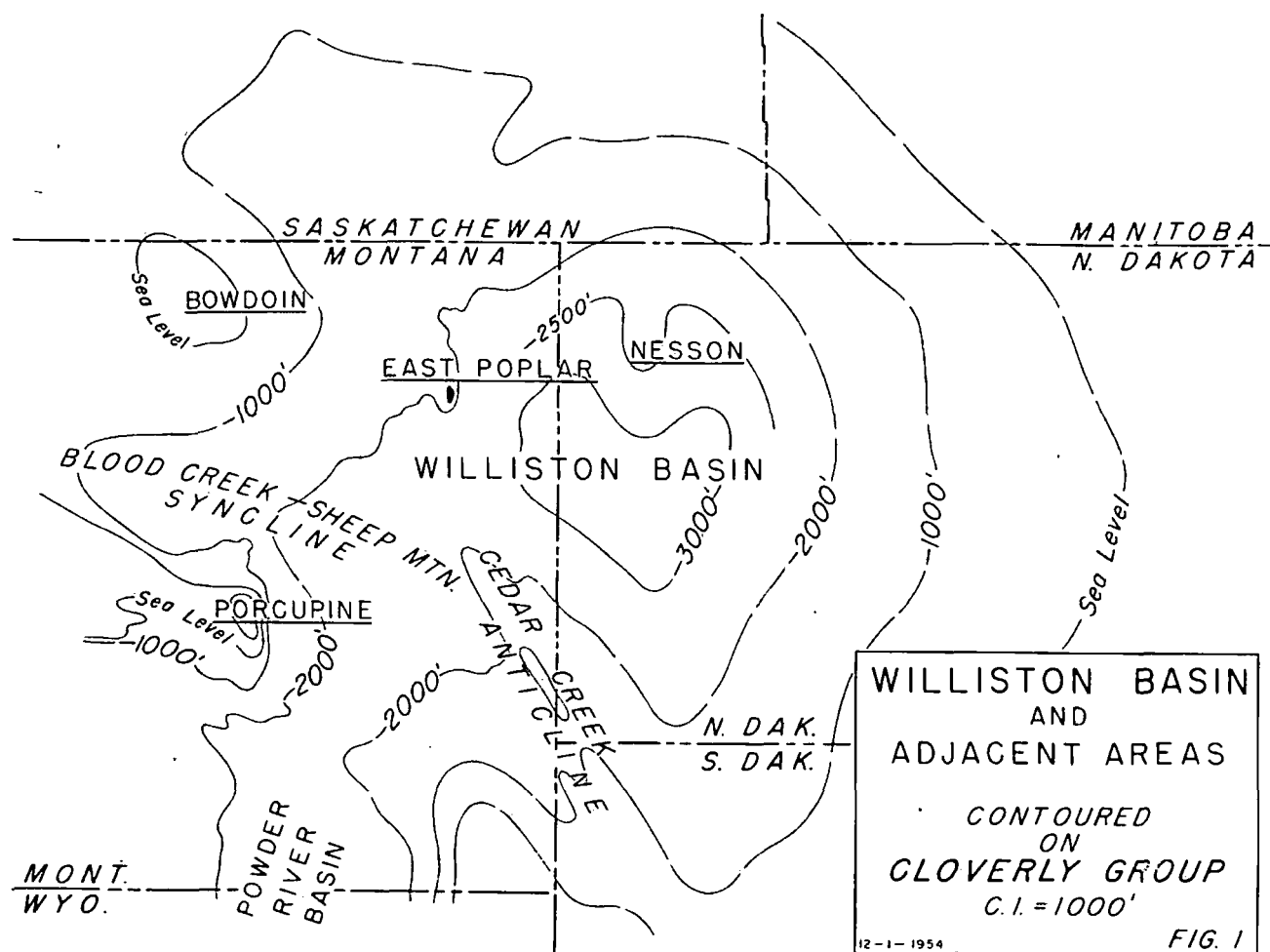
J. B. Powell, Jr.

The author is geologist with Murphy Corporation, headquartered at Billings, Montana and currently primarily active in studies of the East Poplar Field.

He was born at Vivian, Louisiana January 24, 1925, and attended elementary and high school at Vivian. Higher learning included studies at Louisiana State University, Texas University, Oklahoma University and Centenary College. The Bachelor of Science degree in geology was awarded at Centenary and Master of Science in geology at Louisiana State University. He served in the Navy during World War II from 1943 to 1946.

He joined Murphy Corporation in June 1950 serving as geologist in Arkansas, Louisiana, Mississippi, Alabama, Texas, New Mexico and Wyoming prior to moving to Montana in September 1951.

He is a member of the A.A.P.G. and of the Billings Geological Society.



the basis of seismic information (See Figure 2). The well was spudded in September 1951, and in October of the same year drill stem tests of the Mississippian Charles formation at depth intervals of 5664-5682 and 5814-5822 feet recovered substantial amounts of 41° A.P. I. oil. After the first recovery of oil, the well was cored continuously from 5682 to 9163 feet where it was bottomed in the Winnipeg sandstone of Ordovician age. It was then plugged back to a depth of 5827 feet, since no commercial oil shows had been established below the Charles formation. On completion of the well in March 1952, an initial rate of flow of 715 barrels of oil per day through an average 10/64 inch choke was recorded. Production is from 47 feet of perforations and open hole in Charles limestone porosity.

After completion of the discovery well, Unit Operator began a stepout development program of widely spaced wells generally located from one-half to one mile from proven production. The purpose of drilling widely spaced wells was to establish royalty participation for a greater number of landowners at an

early date, to establish proven reserves to encourage market considerations, and to provide reservoir information with which to formulate sound completion practices so as to recover the greatest amount of hydrocarbons economically possible. The stepout program was delayed to some extent by the drilling of several offset wells in a competitive area.

In September of 1952, Well No. 10 Unit was spudded in the SW¼NW¼ Section 30, Township 29 North, Range 51 East, almost 3 miles from proven production. It was classified as a wildcat not only because of its remoteness, but also because seismic data indicated a separate closure in the vicinity. When the well was completed flowing 402 barrels of oil per day from Charles limestone porosity, it was classified as a new discovery. Subsequent development has shown that separate closures do exist, but that the productive area is continuous between No. 10 Unit and No. 1 Unit.

In April 1953, Empire State Oil Company spudded the No. 1 Smith in the SW¼SE¼ Section 8, Township 29 North, Range 51 East, a forty acre offset location

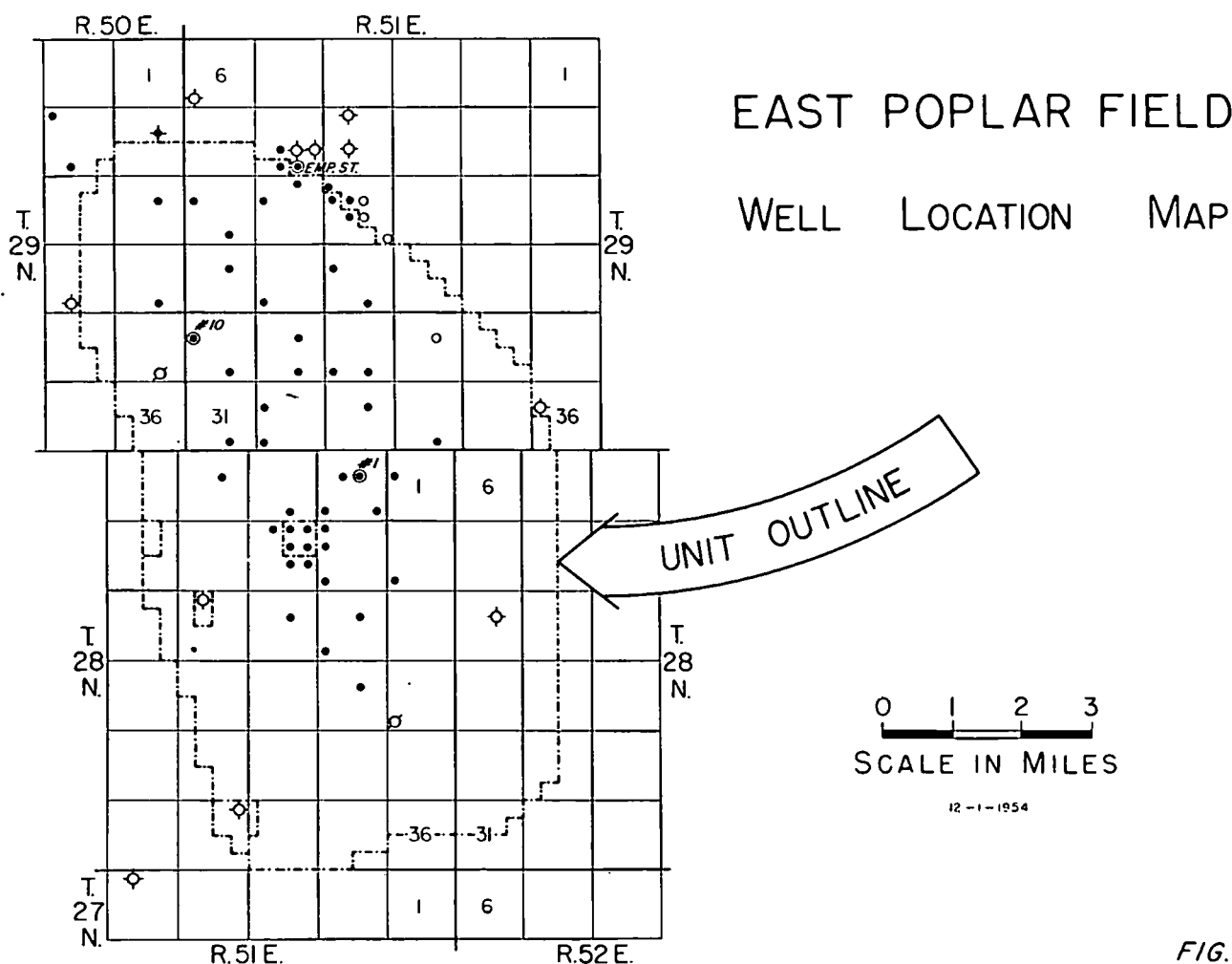


FIG. 2

to the East Poplar Unit Boundary. The well was classified as a wildcat because it was almost two miles from proven production in what was believed to be a decidedly downdip structural position. It was eventually completed as a new discovery flowing at a calculated rate of 6000 (+) barrels of oil per day from the Charles formation. Subsequent development has reasonably proven that the No. 1 Smith simply extended the productive area of the East Poplar field.

As of December 1, 1954 there were 53 oil wells in the field; these wells had proven approximately 15,000 acres to be productive. The field had not been entirely defined on December 1, 1954, and step-out development drilling was continuing.

STRATIGRAPHY

A typical electric log of the field showing the stratigraphic sequence from the surface down below the top of the Mission Canyon is illustrated in Figure 3. The section above the Charles formation is considered typical of the Williston Basin and, conse-

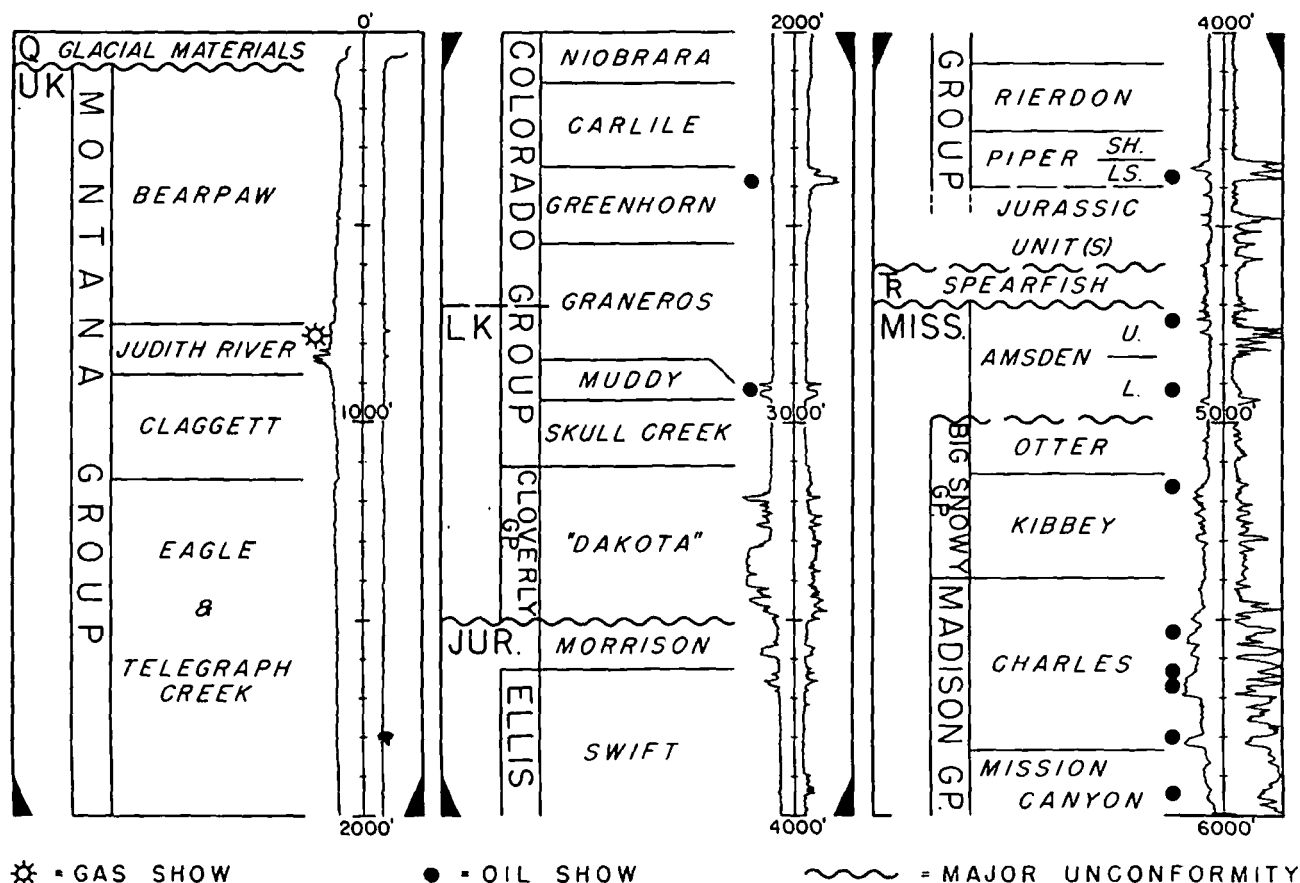
quently, only the units of specific interest will be discussed separately.

In the topographically higher portions of the field, wells usually begin drilling in Pleistocene glacial materials, and go into Upper Cretaceous sediments about 100 feet below the surface. Approximately 2450 feet of Upper Cretaceous sediments are present which are predominantly shales. Lower Cretaceous rocks have an approximate thickness of 950 feet and consist of almost equal percentages of sandstone and shale with some siltstone. Lying unconformably below Lower Cretaceous rocks are approximately 1100 feet of Jurassic sediments which are predominantly gray shale with some red shale, white sandstone, limestone, dolomite, and anhydrite. The Upper Jurassic Morrison formation is believed to be the only unit of fresh water origin in the entire section below the glacial materials.

About 100 feet of Triassic red sands, silts and shale are considered to exist unconformably below Jurassic strata and rest unconformably on Mississip-

TYPICAL E-LOG EAST POPLAR FIELD

FIG. 3



pian sediments. The Mississippian rocks are approximately 2500 feet thick and can be broadly divided into the Amsden formation, Big Snowy group and Madison group. The Amsden is shown as being divided into an upper carbonate unit and a lower clastic unit which is often called Heath. Big Snowy sediments consist of red sandstone, siltstone, and shale, gray and green shales, and a small percentage of limestone. The Madison group is predominantly limestone with some anhydrite, dolomite, shale, and salt occurring in the Charles formation which constitutes the upper 425 feet, more or less, of the group.

Below Mississippian rock, the East Poplar Unit No. 1, deepest well in the field, penetrated 980 feet of Devonian, 200 feet of Silurian and 780 feet of Ordovician sediments which consisted almost entirely of dolomite and limestone, except for the lower 122 feet which was Ordovician Winnipeg sandstone and shale.

As has previously been stated, the producing formation at East Poplar is the Charles. It is com-

posed of interbedded limestone, anhydrite, dolomite, salt and shale in the approximate average proportions of 41 percent limestone, 27 percent anhydrite, 27 percent dolomite, 3 percent salt, and 2 percent shale. The producing porosity zones occur in limestone beds which display both amorphous and crystalline textures. The porosity is manifested in the form of fracture voids, intercrystalline voids and, to a lesser degree, vugs.

Figure 4 is a north-south cross-section of the field area showing the relative position of the main zones of producing porosity. The zones are termed, for convenience, the First, Second, Third, and Fourth Zones of Madison porosity. It can be seen that they are readily recognizable from their characteristic electrical inflections and are persistent throughout the field area.

Probably the most interesting stratigraphic aspect of the East Poplar field is the absence of salt in the Upper Charles, or that interval between the top of the Charles and the First Zone of Madison

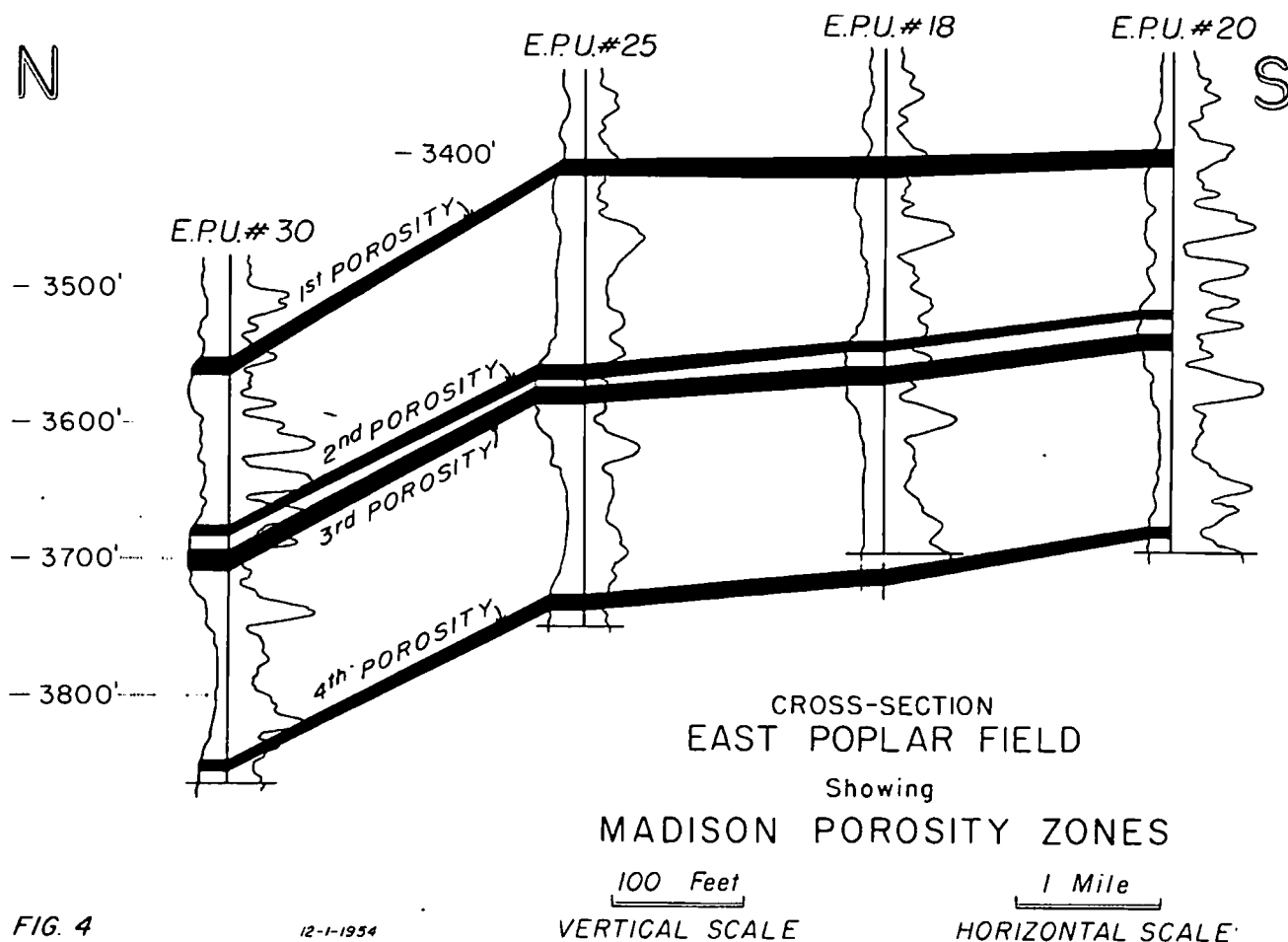


FIG. 4

12-1-1954

Porosity. It is considered normal for wells drilled in the general Poplar area to encounter more than 100 feet of salt in this stratigraphic interval, as is illustrated in Figure 5. The salt occurs in very thin to fairly thick beds which are separated by stringers of dolomite, anhydrite, and shale. Present well control does not permit a precise areal definition of the zero edge of the salt, because a progressive up-flank thinning has not been found on the East Poplar anticline.

The absence of salt on the anticline poses the question as to whether the salt was not deposited in these areas, or was deposited and later removed. The answer to the problem is as yet a matter of speculation since present evidence seems to be inconclusive.

The only production in the field other than that obtained from Charles limestone is from Upper Cretaceous Judith River sandstone at a depth of approximately 850 feet. Three gas wells have been completed in this horizon, each of which produces approximately 50 MCF per day for lease use only. Gas production is not found throughout the entire field area.

It is suspected that the accumulation is controlled to some degree by minor faulting.

Other horizons in which oil shows have been found in the field area are the Greenhorn limestone, Muddy sandstone, Piper limestone, Amsden carbonate, Amsden sandstones, Kibbey sandstone, Mission Canyon limestone, and Devonian dolomites. To date, none of these shows have proven to be of commercial value.

STRUCTURE

The Second Zone of Madison Porosity has been used as a mapping horizon to show the structural configuration of the Charles formation (See Figure 6). A large, slightly asymmetrical anticline having an axial alignment about 25 degrees west of north and east of south is depicted. The feature is at least 11 miles long, and is approximately 6 miles wide. There is approximately 100 feet of mappable closure on this horizon in the field area.

A fairly prominent northeast-southwest trending syncline exists slightly north of the geometric center

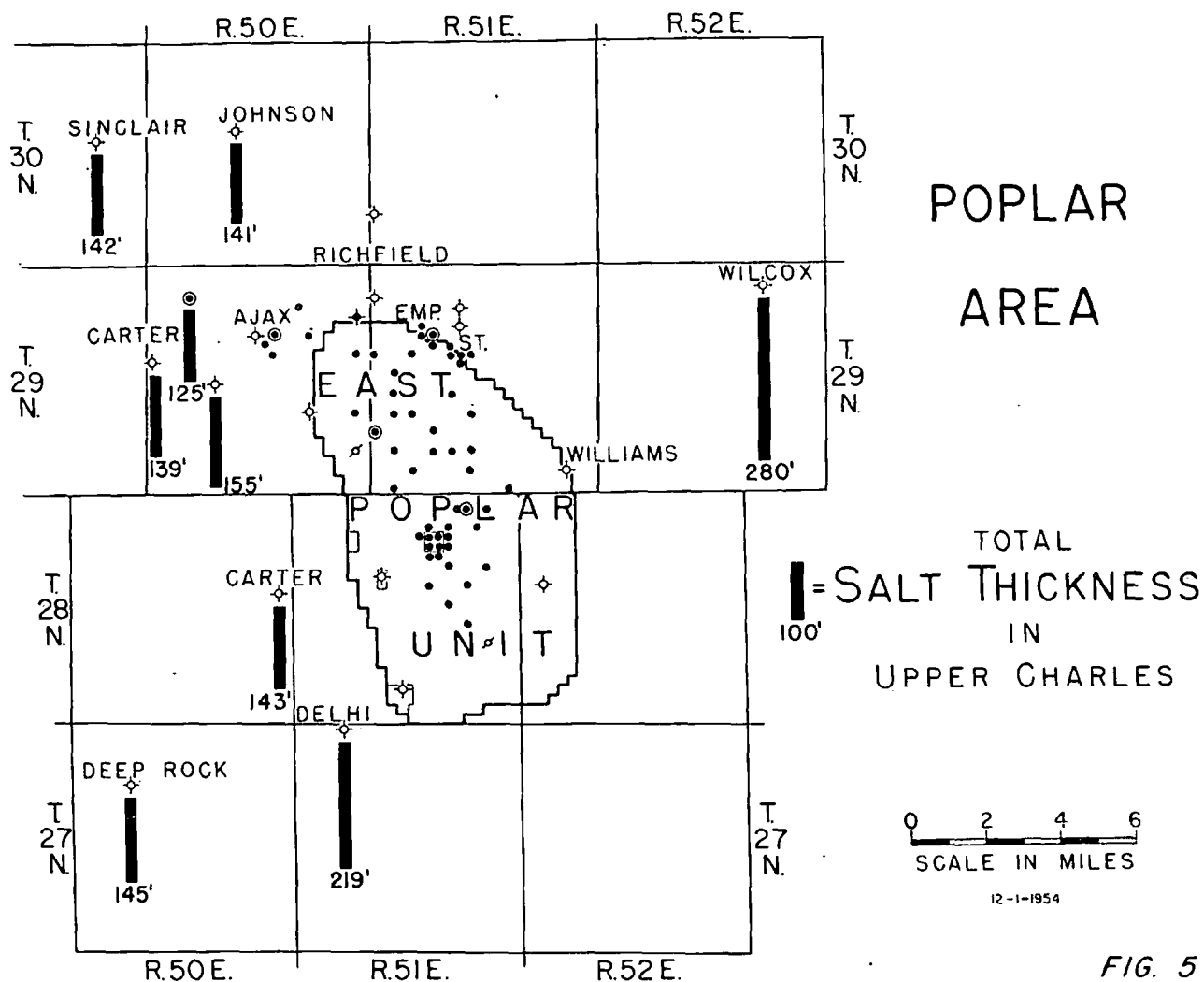


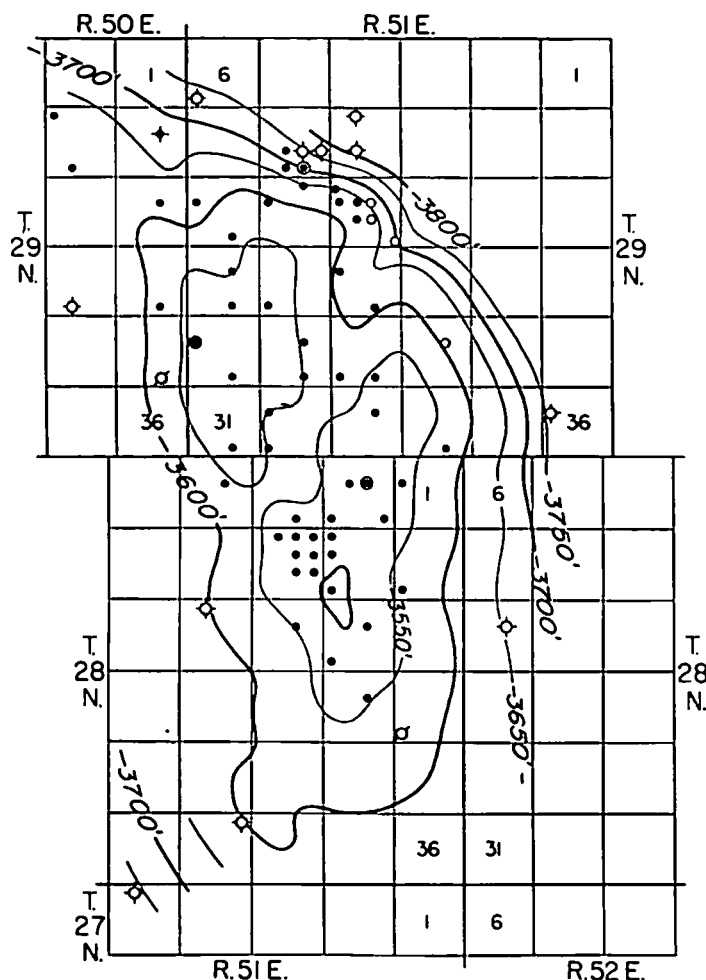
FIG. 5

of the structure, giving rise to separate closures in the northern and southern portion of the field. A secondary alignment is evident in the southern closure which trends slightly east of north and west of south. This alignment is also evident to a lesser extent in the northern closure.

The structural configuration of the Jurassic Piper limestone in the field area is shown in Figure 7. It can be seen that the same general alignment persists in this interpretation as was shown by the Charles interpretation.

The Piper limestone has been found to be the most reliable and persistent seismic reflecting horizon below Cretaceous sediments in the Poplar area. For that reason, seismic maps contoured on the Piper have been used extensively in the stepout development program of the field. Their use in conjunction with a Piper-Second Zone of Madison Poros-

ity isopachous map has proven to be a very valuable aid in predicting Madison structure. Figure 8 is an isopachous map of this interval. It shows, generally, thinning to the northwest, and relatively prominent eastward thickening along the east flank of the structure. The large amount of thickening indicated in the extreme southwest corner of the map area is due to the presence of upper Charles salt in the well in Section 5, Township 27 North, Range 51 East. The maximum amount of variation indicated in the map area is approximately 200 feet. Most of the variation can be attributed to the fact that an angular unconformity exists between Mississippian and Triassic strata. This relationship is shown by the isopachous map presented in Figure 9. It is indicated that the pre-Triassic rocks were tilted to the east and subjected to erosion, so that now only an eastward thinning wedge of Mississippian Amsden remains immediately below the unconformity. The isopach values



STRUCTURE CONTOUR MAP EAST POPLAR FIELD CONTOURED ON 2nd ZONE MADISON POROSITY

CONTOUR INTERVAL = 50'

0 1 2 3
SCALE IN MILES

FIG. 6

used in Figure 9 represent the Amsden thickness plus about 15 feet of Triassic.

The structural configuration of the Cretaceous strata is shown in Figure 10 by contours drawn on top of the Greenhorn limestone.* The primary and secondary alignments that were expressed on the Piper and Second Zone of Madison Porosity structure maps are also evident on the Greenhorn interpretation. There is considerable local variation however, much of which is suspected to be resultant of minor faulting. It is believed that the faulting extends upward through the Judith River sandstone and possibly is a controlling factor of the gas accumulation therein. It is not known how far downward the faulting may extend.

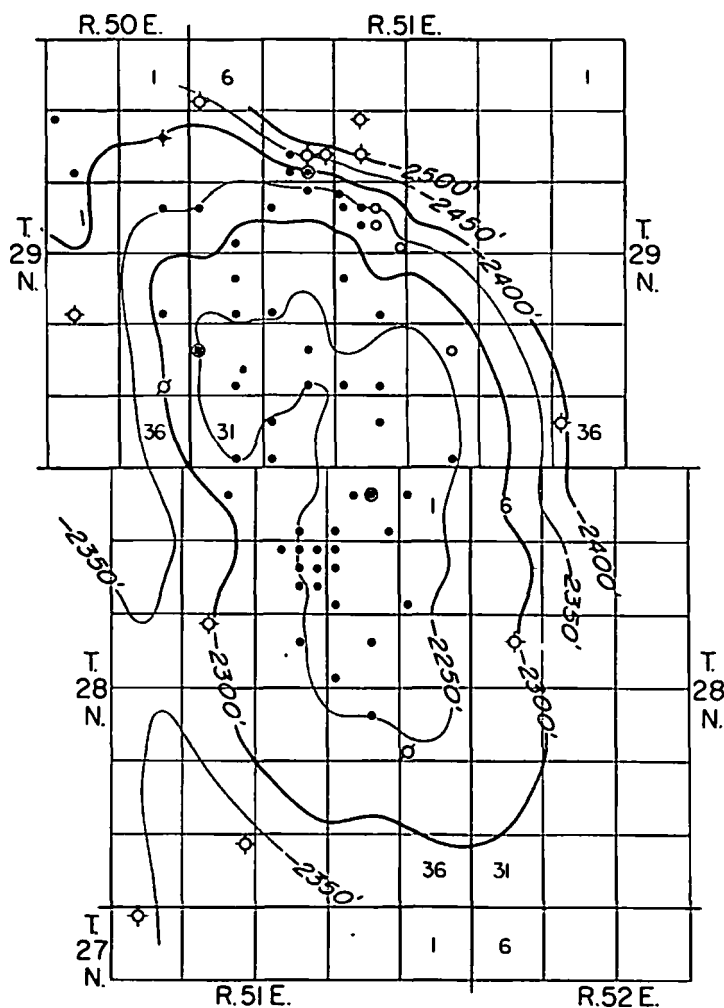
RELATIONSHIP OF ACCUMULATION TO STRUCTURE

The relationship of accumulation to structure is illustrated in Figure 11. As has previously been stated, the productive limits of the field have not been entirely defined; however, enough control ex-

ists at present to adequately demonstrate that the accumulation is partially controlled by porosity variations.

It is presently believed that the only place in the field where a definite oil-water contact has been established is in Section 8, Township 29 North, Range 51 East. Production has been proven down to a subsea depth of 3727 feet on the Second Zone of Madison porosity in this local area, and water has been established at 3744 feet, subsea, in the same area. Consequently, the 3727 foot, subsea, contour on the Second Porosity represents the local outward limit of proven production. How far this 3727 foot, subsea, lowest level of production will maintain itself in a northwestward and southeastward direction is not known.

The limit of production to the northwest is apparently governed by permeability. The well in Section 6, Township 29 North, Range 51 East, and the wells in Sections 11, 12, 24, and 25, Township 29



STRUCTURE CONTOUR MAP EAST POPLAR FIELD

CONTOURED
ON
PIPER LIMESTONE

CONTOUR INTERVAL = 50'

0 1 2 3
SCALE IN MILES

12-1-1954

FIG. 7

North, Range 50 East, furnished proof of permeability decrease, or effective permeability pinchout, in zones of Madison porosity.

The southwest edge of the field area is limited by the wells in Sections 16 and 33, Township 28 North, Range 51 East. Both wells are located structurally higher with respect to a number of producers in the north end of the field, but both established water in the Madison reservoir.

To the southeast, accumulation is limited by the well in Section 24, Township 28 North, Range 51 East and the well in Section 18, Township 28 North, Range 52 East. These wells were also located structurally high with respect to some producers in the north end of the field. They failed to establish production because of very low permeability and high water saturation in the Madison porosity zones. In reference to the southern portion of the field, it should be mentioned that the southernmost six oil wells have produced excessively high percentages of

water from the time of their completion until the present.

The well in Section 36, Township 29 North, Range 51 East, limits the accumulation on the east side of the central portion of the field. Very good porosity and permeability were evidenced in Madison zones of porosity in this well by substantial recoveries of water on drill stem tests. It is believed that the well is located structurally too low to produce, being 40 feet lower than the lowest established level of production.

From these facts, it is apparent that the accumulation is partially controlled by porosity variations. It is not apparent at the present time, however, whether porosity control is complete and, if not, what additional factors are directly involved.

RESERVOIR DATA

Porosity	11 percent
Permeability	5 Millidarcies

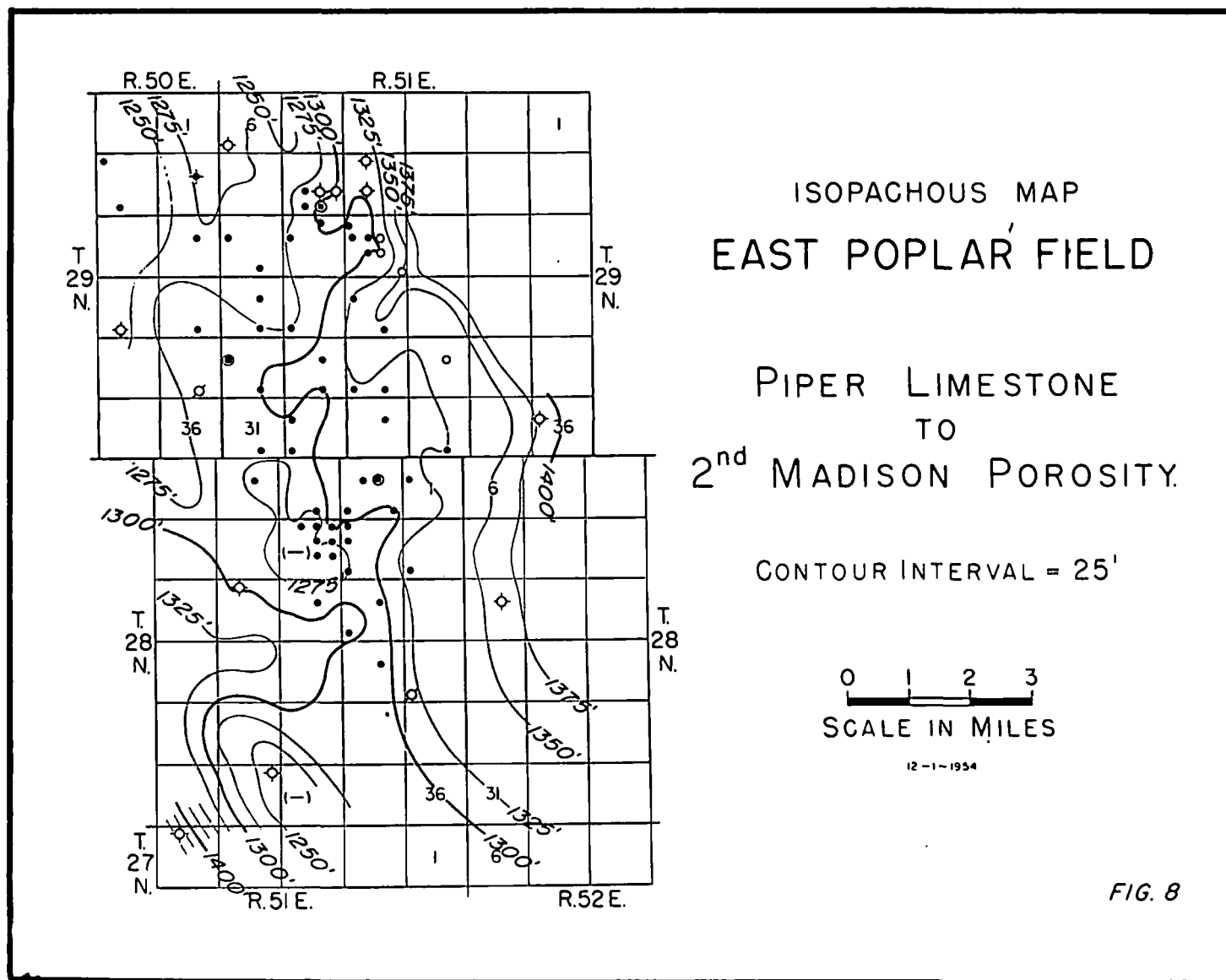


FIG. 8

ISOPACHOUS MAP
EAST POPLAR FIELD

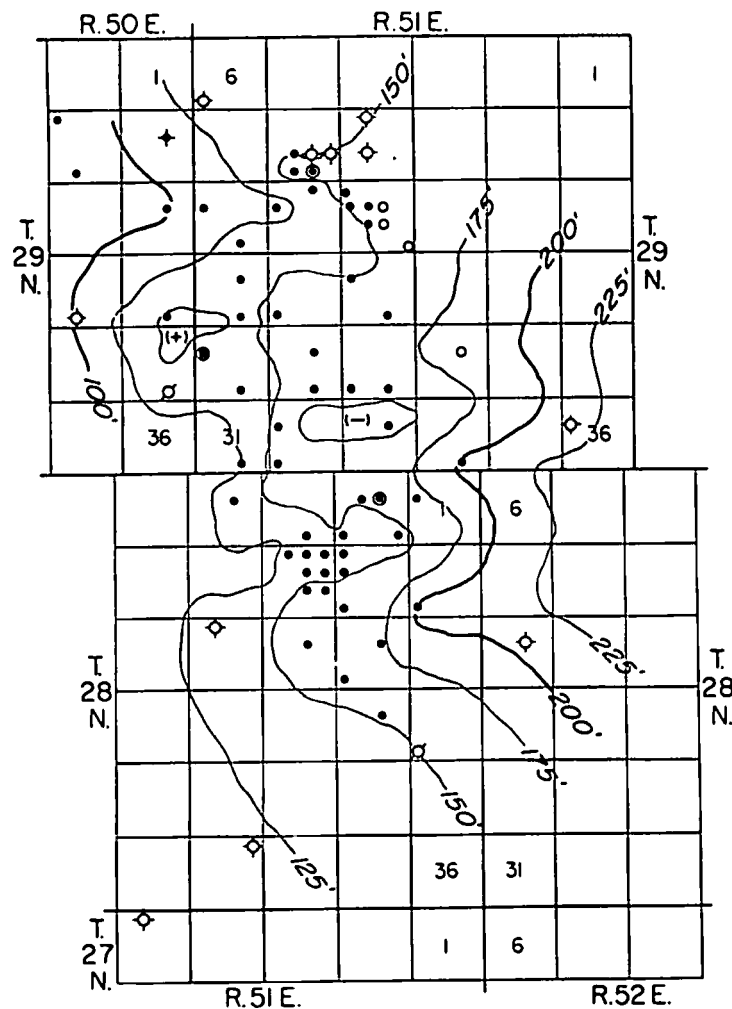
TRIASSIC MARKER
TO
BASE AMDSEN CARBONATE

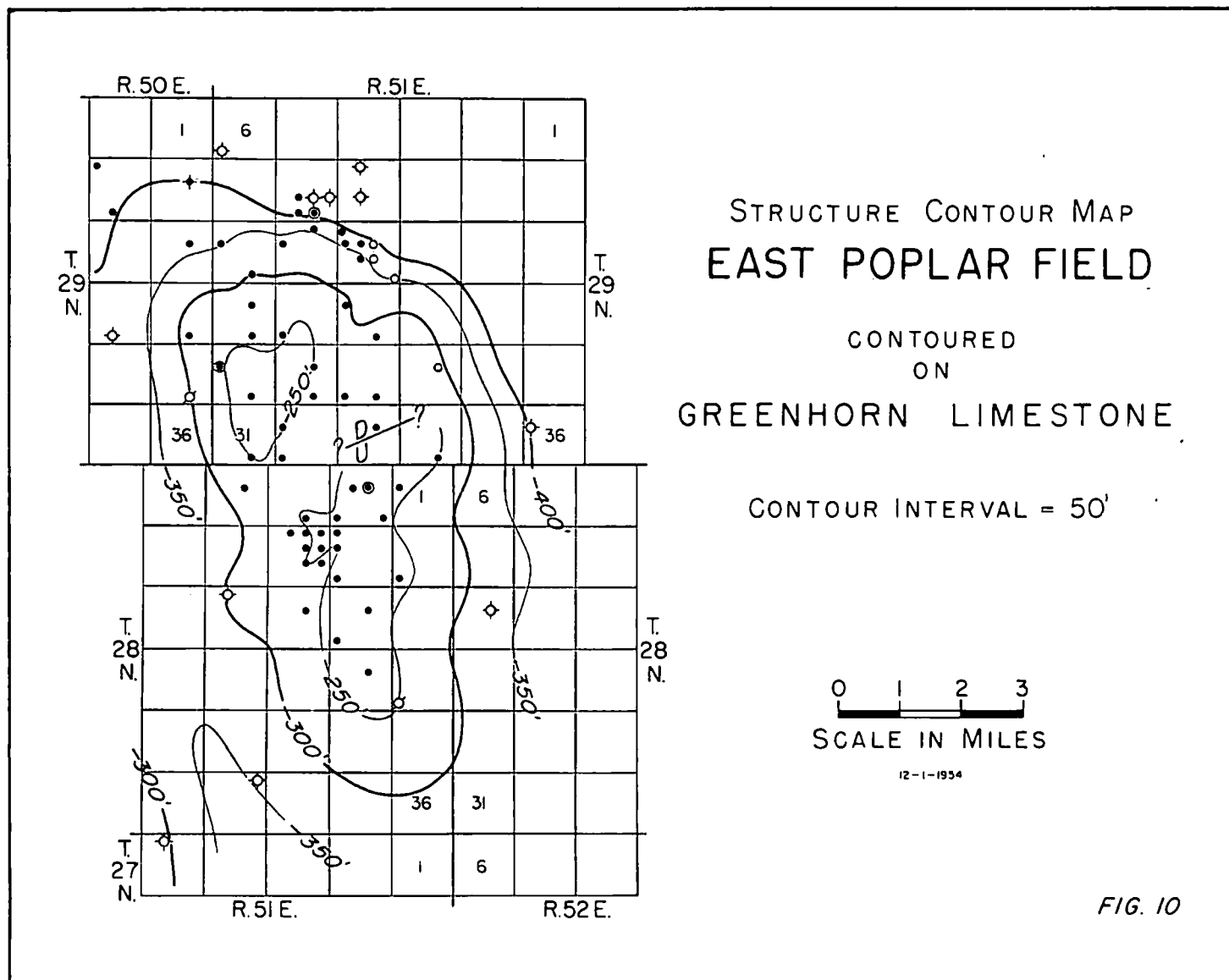
CONTOUR INTERVAL = 25'

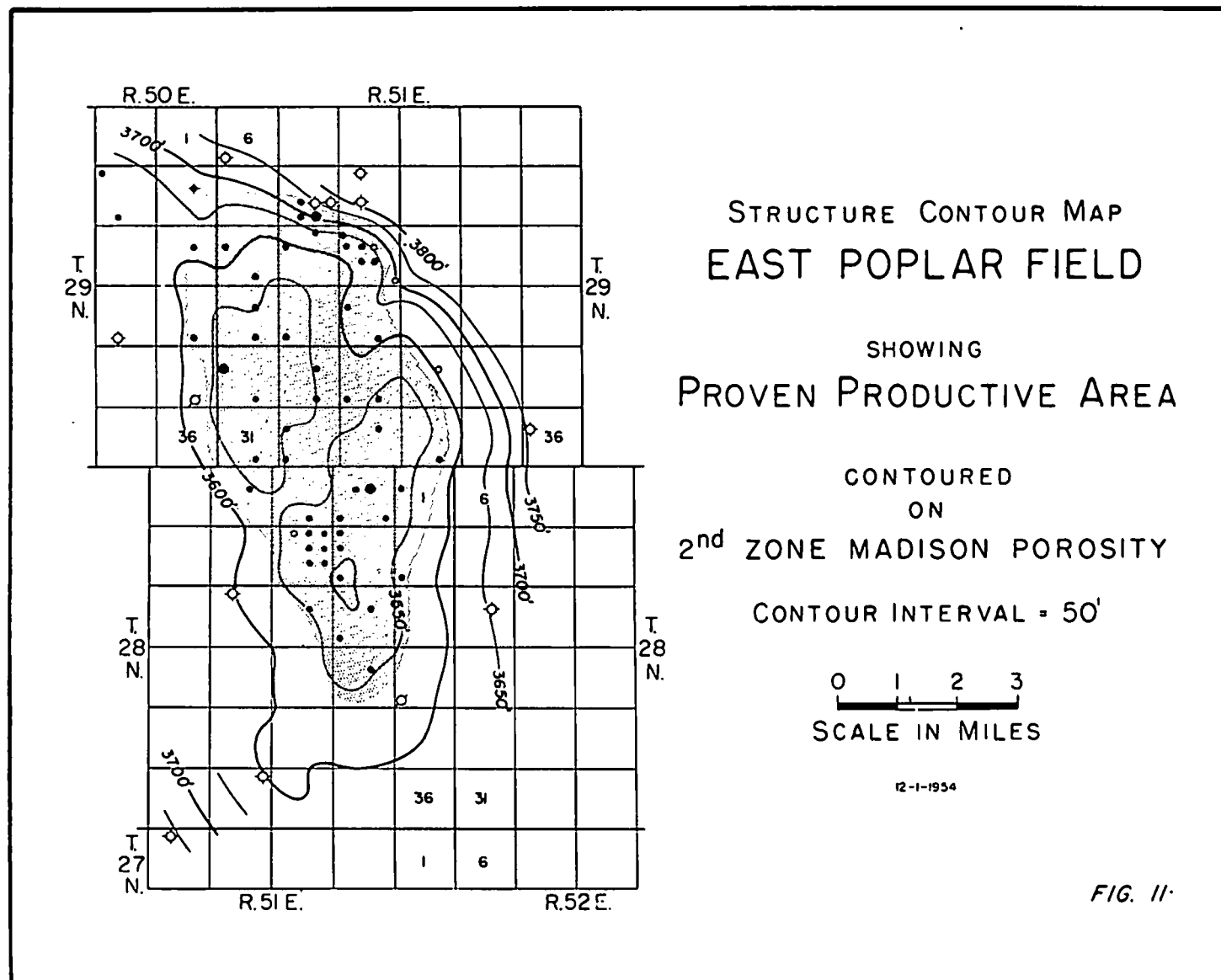
0 1 2 3
SCALE IN MILES

12-1-1954

FIG. 9







Connate Water	30 percent
Average Net Pay Thickness	35 feet
Gas-Oil Ratio	20 cubic feet per barrel
Initial Bottom Hole Pressure @-3550'	2940 p.s.i.g.
Bottom Hole Temperature @3550'	246° F.
Gas-Oil Contact	None
Water-Oil Contact	Irregular
Recovery Mechanism	Water drive
Present Productive Area (12-1-54)	15,000 acres
Estimated Recoverable Reserves	60 million barrels*

*This figure is presented in an attempt to place the East Poplar field in proper perspective as regards reserves because of recently published erroneous information pertaining to oil in place. This figure is believed to represent a reasonable estimate; however,

for obvious reasons it is presented with reservations.

CRUDE CHARACTERISTICS

Type	Paraffin base
Color	Brownish green
Gravity °A.P.I. @60° F.	40.2
Sulphur Percent	0.37
Pour Point °F.	+15
SUV @70° F.	40.6
SUV @100° F.	36.8
Initial Boiling Point °F.	87

PRODUCTION

Spacing	40 - 160 acres
Estimated Average I.P. (¼" Choke)	250 + BOPD
Cumulative Production (12-1-54)	4,173,866 barrels

DEPARTMENT NATURAL RESOURCES & CONSERVATION

BOARD OF OIL & GAS CONSERVATION

THOMAS L. JUDGE, GOVERNOR

OIL & GAS CONSERVATION DIVISION

TED J. DONEY, DIRECTOR



EAST POPLAR FIELD AREA
ROOSEVELT COUNTY, MONTANA

O. A. LIEN COMPLAINT

SEPTEMBER 24, 1979

Andrew R. Fish
Petroleum Engineer

DIVISION OFFICE
25 SOUTH EWING
P.O. BOX 217
HELENA, MONTANA 59601
(406) 449-2611

TECHNICAL AND
SOUTHERN FIELD OFFICE
2535 ST. JOHNS AVENUE
BILLINGS, MONTANA 59102
(406) 658-0040

NORTHERN FIELD OFFICE
218 MAIN STREET
P.O. BOX 690
SHELBY, MONTANA 59474
(406) 434-2422

EAST POPLAR FIELD AREA
ROOSEVELT COUNTY, MONTANA

O. A. LIEN COMPLAINT

SEPTEMBER 24, 1979

INTRODUCTION AND HISTORY

Location

The East Poplar Unit is a Federally supervised oil field lying primarily in T28N-R51E and T29N-R51E, Roosevelt County, Montana, and which is under jurisdiction of the United States Geological Survey. Adjacent to and surrounding the EPU are additional productive lands, some of which are part of the Fort Peck Indian Reservation and some of which are held in fee. Whereas the Indian land also falls under Federal jurisdiction, the fee lands are administered by the Montana Department of Natural Resources, Oil and Gas Division. Oil field operations have been conducted in this area since the early 1950's.

Purpose

On July 23, 1979, Mr. Joe M. Simonson and Mr. A. R. Fish, Jr., of the Oil and Gas Board and Mr. Dayton Alsaker of the Department of Health, Water Quality Bureau conducted a field inspection of the area in response to a complaint by Mr. Orphey (Bud) lien of Poplar, Montana. Mr. Lien asserted that Murphy Oil Corporation, the major operator in T29N-R51E has consistently and for several years been negligent in its production operations to the extent that they have allowed crude oil and produced connate water to contaminate the ground surface and shallow fresh water aquifer. Mr. Lien stated that the contamination has substantially reduced his suitable land for farming and degraded the majority of the fresh water aquifer to the

point that it can no longer be used for domestic consumption or readily used for irrigation.

FINDINGS

Water Quality

Samples were taken from nine separate locations by Mr. Alsaker for analysis by his office. An additional sample taken by Mr. Simonson in 1975 is included for comparison. Sample points were selected to include all wells drilled by Mr. Lien for fresh water, surface water containing only background ions, and produced connate water. Each sample point is described below and is referred to Appendix A, Table I.

Sample #1: Taken from the pit formerly associated with "M" Battery which no longer is in place. The pit had not been used for more than two years and had only a small amount of rain water in the bottom of it. Some aquatic insects and limited vegetation were evident.

Sample #2: Taken from the domestic supply well for the Lien household. This well is used for water needs other than drinking and is reported to have become less usable with time.

Sample #3: Taken from the same source as Sample #2, but in March, 1975.

Sample #4: Taken from a well drilled in search of irrigation water.

Sample #5: Taken from the well which provides all domestic water for a tenant on the Lien property as well as drinking water for the Lien household. The depth of this well (12 feet), along with its close proximity to the Poplar River make it probable that water in the well is part of the natural flow of the stream through the stream bed gravel. This probability is corroborated in Figure 1, the tri-linear plot of water analyses.

Sample #6: Taken from a well drilled in search of irrigation water. This water was cloudy and had a notable iron taste.

Sample #7: Taken from a well drilled for irrigation/domestic water. This water was dark grey in color and had distinct iron taste.

Sample #8: Taken from the Poplar River upstream from the EPU and geographically prior to oil field operations.

Sample #9: Taken from the disposal system at Murphy Oil's Salt Water Station #1. This should be indicative of produced connate water.

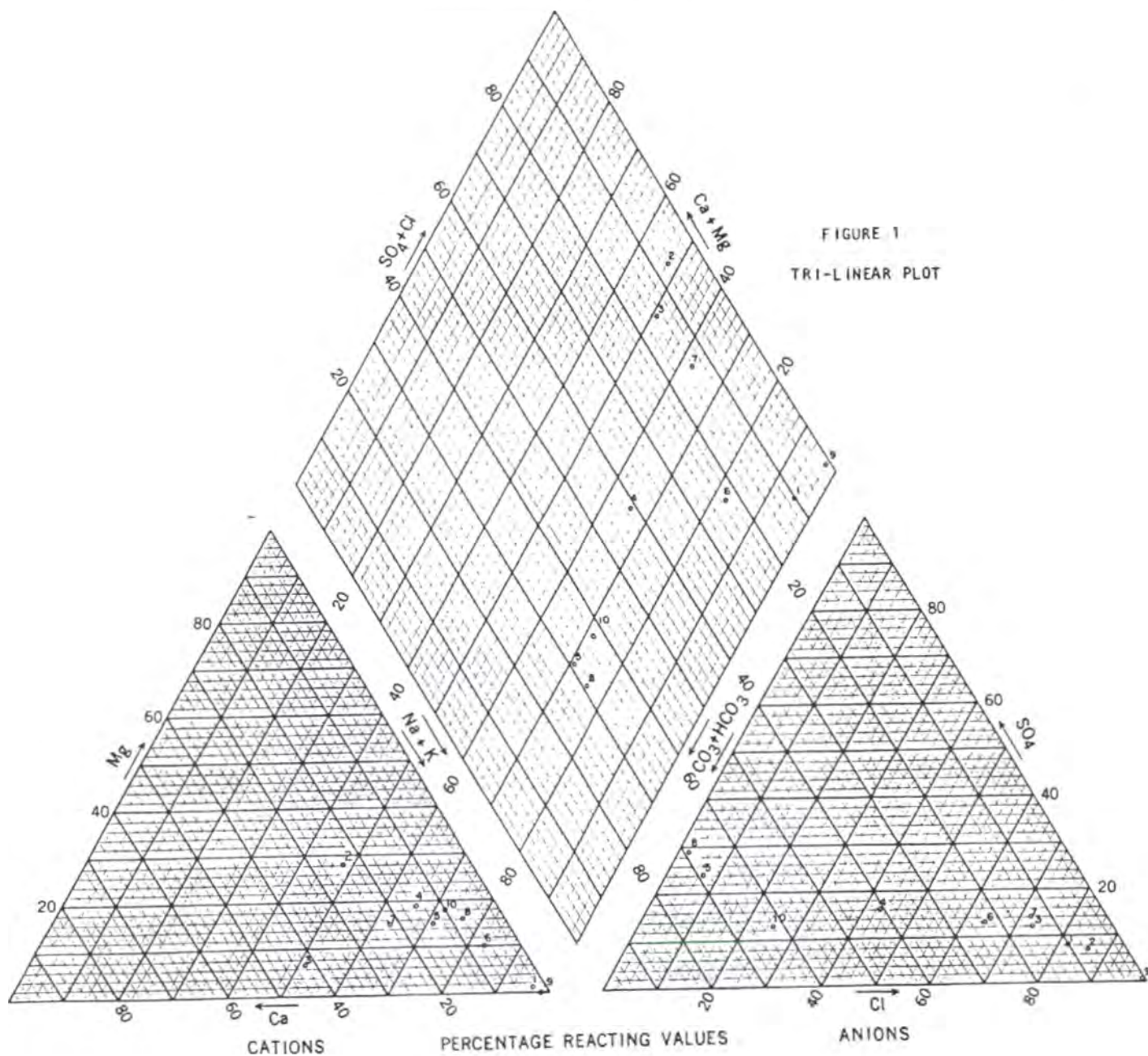
Sample #10: Taken from the Poplar River at a point two miles within the EPU.

The results of chemical analysis of each sample are tabulated in Appendix A, Table I, as parts per million (ppm) and the geographic distribution of the sample points is plotted on the partial field map which is pocketed with this report. The chloride ion concentration, considered the prime indicator in this study, is given alongside each sample point on the map.

The ppm amounts of dissolved solids from each sample were normalized to weight percent of each ion by the milliequivalent technique, which is a recognized technique for comparing, on an equal basis, waters of varying ionic concentrations. The constants of equivalent weight used in computations are presented in Appendix A, Table II. Multiplying the ion concentration in parts per million by the appropriate factor from Table II yields the milligram equivalents per liter of solution for each ion (Meq./L.). These milligram equivalents, presented in Appendix A, Table III, can then be converted to percent of each ion in each sample for direct and equal comparison. The milliequivalent percent of each ion in each sample is presented in Appendix A, Table IV, and plotted on the tri-linear diagram, Figure 1.

A tri-linear diagram is useful when mixing of two waters is suspected. The diagram consists of a chemical balance triangle for the common anions (negatively charged ions) and a second triangle for the common cations (positively charged ions) along with a

WATER-ANALYSIS DIAGRAM



central diamond shaped area which shows the overall chemical character of the water. Several samples of separate and unmixed water types will plot as unassociated groups of points on the anion and cation triangles while samples which are the product of the mixing of two waters will exhibit a trend line on one or both triangles. The central diamond can be subdivided to indicate basic water type. These subdivisions are the four small diamonds bounded by the 50% cation - anion pair concentration lines. Samples 5, 8, and 10 are alone in one subdivision and represent the river water samples along with the usable domestic well. The remainder of the samples are in another subdivision which characterizes brines of greater or lesser concentration.

The following conclusions can be drawn from the tri-linear plot:

- (1) The trend line of increasing chloride (the indicator) suggests mixing in varying amounts of the water types of Sample #9, the produced connate water and the water types of Sample #5 or #8 the ground water.
- (2) The concentration of chloride in the surface water increased from 1975 to 1979 (see Samples #2 and #3).
- (3) The concentration of chloride in the river increases as the river passes into the EPU (see Samples #8 and #10).
- (4) The domestic source well of Sample #5 is producing essentially river water (see grouping in one quadrant).

Field Activities

Although the primary subject of this investigation was ground water quality and possible pollution, certain operational problems should be addressed. Problem areas have been separated into two categories of responsibility which are: (a) State of Montana-Oil and Gas Board, and (b) Federal-

U. S. Geological Survey. The East Poplar Unit is shown on the map, Figure 1, by heavy, solid outline. Generally speaking, wells located outside the unit boundary are administered by the Montana Oil and Gas Board while the U.S.G.S. is the regulatory agency for the lands within the unit.

The following is a list of substandard locations together with recommended remedial action:

State Jurisdiction:

- (1) SW/4 SE/4 Section 8-T29N-R51E

Murphy #1 Smith

This location appears to be temporarily abandoned. Necessary remedial action includes filling the pit associated with this well, determining the source of and stopping the flow of gas bubbling through the oil in the cellar, removing all fluid in the cellar, and cleaning the location of all debris. If this well has no further economic value the location should, in the interest of the surface owner, be permanently abandoned and the land restored to productive capability.

- (2) SE/4 SE/4 Section 16-T29N-R51E

Murphy #1 Owens

This former salt water injection well appears to have been in a state of temporary abandonment for some time. Debris should be cleared from the location and/or the location permanently abandoned if the well has no further economic value.

- (3) SW/4 NE/4 Section 16-T29N-R51E

Empire State #6 Martin

Although permanently abandoned, this location still needs to have the pump base buried and a "dead man" anchor removed.

(4) NE/4 NW/4 Section 16-T29N-R51E

Murphy #7 Rehder

This permanently abandoned location should have the remaining pit filled.

Federal Jurisdiction:

(1) SE/4 SE/4 Section 17-T29N-R51E

"M" Battery (?)

This appears to be the former location of "M" Battery. A small pit is still in existence and should be filled.

(2) SE/4 SE/4 SE/4 Section 30-T29N-R51E

Salt Water Station #1

The large pit associated with this water injection well and battery should be cleaned of oil and either properly lined or filled. Surface injection equipment is in a marginal state of repair with evidence of numerous previous leaks. Necessary maintenance to preclude further leaks should be performed.

It should be noted that since the Oil and Gas Board has no direct authority within the EPU, no concerted study was made of operational problems within the unit.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been made regarding the study area:

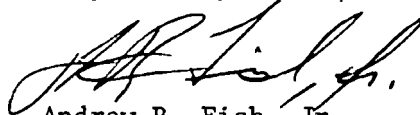
(1) The quality of the ground water in the area of the East Poplar Unit, especially within the unit boundary, appears to have been degraded. Chloride ion concentration has increased with time in at least one domestic source well and also increases with distance downstream in the Poplar River within

the unit boundary as well as with distance away from the river. The fresh aquifer appears to be a perched water table overlying the Bearpaw shale and has possibly been contaminated by spills and seepage from pre-existent evaporation and/or emergency pits as well as leaks which have developed in salt water lines. Photographs furnished by Mr. Lien point out numerous spills and leaks of both salt water and crude oil. These photos are corroborated by marked reduction in productivity of the affected lands as noted during the inspection. Since most of the damage has occurred within the EPU boundary it would be logical for U.S.G.S. to independently evaluate the situation and closely monitor future activities of the operators.

(2) Murphy Oil Corporation, as principle operator in the area, is hereby directed to immediately respond to this study and proceed with the restoration/reclamation of the operational deficiencies heretofore enumerated under Oil and Gas Board jurisdiction. Efforts of this nature are in the best interest of oil industry-landowner relations.

(3) The aforementioned operational problems should be remedied within 90 days of the date of this report or reasons presented as to why such remedial work is impractical.

Respectfully submitted,

A handwritten signature in dark ink, appearing to read 'A. R. Fish, Jr.', is written over the typed name.

Andrew R. Fish, Jr.
Petroleum Engineer

ARF:er

APPENDIX A

TABLE I

WATER SAMPLE RAW DATA

SAMPLE NO.	DATE	LOCATION	Ionic Content (ppm)					
			HCO ₃ ⁻	Cl ⁻	SO ₄ ⁻⁻	Mg ⁺⁺	Ca ⁺⁺	Na ⁺
1	7/23/79	SE SE Sec. 17-T29N-R51E	183.0	862.0	114.0	3.8	17.2	671
2	7/23/79	NW NE Sec. 20-T29N-R51E	309.9	2,190.0	225.0	242.0	340.0	790
3	3/4/75	NW NE Sec. 20-T29N-R51E	381.0	1,086.0	250.0	36.0	350.0	485
4	7/23/79	SE NE Sec. 17-T29N-R51E	389.2	230.0	115.0	34.7	46.7	228
5	7/23/79	SW NW NE Sec. 21-T29N-R51E	553.9	33.5	152.0	24.1	38.0	215
6	7/23/79	NE NW NW Sec. 21-T29N-R51E	380.6	629.0	177.0	31.7	39.4	526
7	7/23/79	SW SW SW Sec. 17-T29N-R51E	79.5	238.0	64.2	17.1	40.2	132
8	7/23/79	SW SE Sec. 9-T29N-R51E	507.5	7.9	165.0	23.7	19.2	207
9	7/23/79	SE SE Sec. 30-T29N-R51E	170.8	106,000.0	1670.0	141.0	1,480.0	68,600
10	7/23/79	SE NE Sec. 31-T29N-R51E	499.0	116.0	80.5	29.4	26.7	224

TABLE II

TABLE OF EQUIVALENT WEIGHTS*

Ion	Equivalent Wt. x 10 ⁻¹
Bicarbonate (HCO_3^-)	0.01639
Chloride (Cl^-)	0.02821
Sulfate (SO_4^{--})	0.02082
Magnesium (Mg^{++})	0.08226
Calcium (Ca^{++})	0.04990
Sodium (Na^+)	0.04350

*Based on 1961 atomic weights as referred to Carbon -12.

TABLE III

WATER DATA ANALYSIS - I

SAMPLE NO.	Milligram Equivalents/Liter (Meq./L.)						Totals	
	HCO ₃ ⁻	Cl ⁻	SO ₄ ⁻⁻	Mg ⁺⁺	Ca ⁺⁺	Na ⁺	Anions	Cations
1	3.00	24.31	2.37	0.31	0.86	29.19	29.68	30.36
2	5.08	61.76	4.68	19.92	17.00	34.37	71.52	71.29
3	6.25	30.63	5.20	2.96	17.50	21.10	42.08	41.56
4	6.38	6.49	2.39	2.86	2.34	9.92	15.26	15.12
5	9.08	0.94	3.16	1.98	1.90	9.35	13.18	13.23
6	6.24	17.74	3.68	2.61	1.97	22.88	27.66	27.46
7	1.30	6.71	1.34	1.41	2.01	5.74	9.35	9.16
8	8.32	0.22	3.43	1.95	0.96	9.00	11.97	11.91
9	2.80	2889.20	34.74	11.60	74.00	2984.10	3026.70	3069.70
10	8.18	3.27	1.67	2.42	1.34	9.74	13.12	13.50

TABLE IV
WATER DATA ANALYSIS - II

SAMPLE NO.	Milligram Equivalent Percent (Meq. %)					
	HCO ₃ ⁻	Cl ⁻	SO ₄ ⁻⁻	Mg ⁺⁺	Ca ⁺⁺	Na ⁺
1	10	82	8	1	3	96
2	7	86	7	28	24	48
3	15	73	12	7	42	51
4	41	43	16	19	15	66
5	69	7	24	15	14	71
6	23	64	13	10	7	83
7	14	72	14	15	22	63
8	69	2	29	16	8	76
9	0	99	1	0	2	98
10	62	25	13	18	10	72

(4000) 768
3612

G. Stoltz
1/2/86 bfr

Underground Injection Activities
into the Judith River Formation
on the Fort Peck Reservation.

Statement of Policy &
Technical Evaluation.
December, 1985

U. S. ENVIRONMENTAL PROTECTION AGENCY
REGION VIII

One Denver Place - Suite 1300
999-18th Street
Denver, Colorado 80202-2413



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION VIII
ONE DENVER PLACE — 999 18TH STREET — SUITE 1300
DENVER, COLORADO 80202-2413

PUBLIC NOTICE
UNDERGROUND INJECTION CONTROL PROGRAM

FINAL DETERMINATION

**Injection into the Judith River Formation
on the Fort Peck Reservation**

PURPOSE OF PUBLIC NOTICE

The purpose of this notice is to inform interested parties that:

- (1) the U.S. Environmental Protection Agency (EPA) has developed a policy regarding the issuance of Underground Injection Control (UIC) permits on the Fort Peck Reservation for disposal of fluids into the Judith River Formation; and
- (2) EPA has made a determination to issue a final UIC permit for the Goings No. 1 Salt Water Disposal Well, located in the Poplar Field and operated by Century Oil & Gas.

BACKGROUND

EPA held a hearing on May 29, 1985, upon request of the Fort Peck Tribes, to gather factual information regarding hydrogeologic characteristics of the Judith River Formation, and to allow comments to be heard concerning EPA's intent to issue a UIC permit for continuation of salt water disposal into the Goings No. 1 Well. The Goings No. 1 Well is one of several disposal wells injecting fluids into the Judith River Formation. The Tribe has requested that the Judith River Formation be protected as an underground source of drinking water (USDW). The Goings No. 1 well was injecting prior to the inception of the UIC program (June 25, 1985), and is therefore classified as an existing well authorized by rule.

FINAL DECISIONS

A statement has been prepared which establishes EPA's policy on permitting existing and future wells that inject into the Judith River Formation on the Fort Peck Reservation. A copy of EPA's Statement of Policy is being sent concurrently with the publication of this notice to all attendees of the hearing as well as all persons who may be affected by the outcome of such a policy.

In addition, EPA has also made a final permit determination for the Goings No. 1 Well permit application. In the time period since the draft permit was issued in December, 1984, the Goings No. 1 Well failed a mechanical integrity test, was reworked to repair casing defects, and subsequently, passed a retesting of mechanical integrity. It has been determined that the well meets all UIC requirements and does not pose a threat to any underground source of drinking water. Therefore, a final permit is being issued on the date of publication of this notice with no changes from the draft permit. Upon issuance of the permit, authorization to inject into the Goings No. 1 Well will be transferred from rule to permit. This action is consistent with the policy mentioned above.

PERMIT APPEAL PROCESS

Within 30 days after a UIC final permit decision has been issued, any person who filed comments on that draft permit or participated in the public hearing may petition the Administrator of EPA to review any condition of the permit decision. Commentors are referred to 40 CFR 124.19 for procedural requirements of the appeal process.

FOR MORE INFORMATION

The Administrative Record for these actions contains:

- (1) the Goings No. 1 permit application, draft and final permits;
- (2) the official transcript of the hearing;
- (3) EPA's technical evaluation of the testimony presented at the hearing; and
- (4) EPA's Statement of Policy regarding injection activities and the Judith River Formation on the Fort Peck Reservation.

For further information, you may contact the following offices:

A. Concerning the Judith River Policy:

Environmental Protection Agency
Region VIII
Drinking Water Branch 8WM-DW
One Denver Place, Suite 1300
999-18th Street
Denver, Colorado 80202-2413

ATTN: Debra G. Ehlert
Telephone: (303) 293-1415

B. Concerning the Going No. 1 Permit:

Environmental Protection Agency
Montana Office
Federal Office Building
Drawer 10096
301 South Park
Helena, Montana 59626

ATTN: Jim Boyter
Telephone: (406) 449-5486

DEC 9 0 1985

Date of Publication



Max H. Dodson, Director
Water Management Division



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION VIII
ONE DENVER PLACE — 999 18TH STREET — SUITE 1300
DENVER, COLORADO 80202-2413

Statement of Policy

Injection activities into the Judith River Formation
on the Fort Peck Reservation

BACKGROUND

EPA published a notice on December 27, 1984, in the Wolf Point Herald stating an intent to issue two Underground Injection Control (UIC) permits to Century Oil & Gas for the purpose of salt water fluid disposal. EPA encouraged public comments on the proposed actions. A notice appearing on January 15, 1985, extended the deadline for public comments on EPA's intended actions until February 15, 1985.

In a letter of January 29, 1985, the Fort Peck Tribes objected to the issuance of one of the two draft UIC permits which would allow injection through the Goings No. 1 Well. The objection was based on the Tribe's overall concern about the degradation of ground water on the Reservation. The Goings No. 1 Well is one of several injection wells which presently disposes of fluids into the Judith River Formation — an aquifer which the Tribe has requested be protected as an underground source of drinking water (USDW). The UIC regulations broadly define a USDW as an aquifer or its portion which both: 1) contains fewer than 10,000 mg/l total dissolved solids (TDS), and 2) is capable of supplying a public water system.

The Tribe subsequently requested a public hearing in order to present relevant information which would substantiate their request to preserve the Judith River Formation. The hearing was held on May 29, 1985, at the Poplar Activity Center.

CONCLUSIONS

The testimony and supporting documentation collected at the hearing were evaluated by EPA. The following discussions reflect the results of the technical evaluation and constitute EPA policy.

POLICY
STATEMENT
NO. 1

No new injection wells or converted wells will be allowed to dispose of fluids into the Judith River Formation where the TDS concentration is known to be less than 10,000 mg/l.



Discussion and Basis of Decision

Alternative sources of drinking water are currently available and are being used in the vicinity of the oil production. The principal sources (alluvium and glacial gravels; the Fox Hills and Fort Union aquifers) are located stratigraphically above the Judith River and have significantly higher quality water. The Judith River provides water for livestock use near the cities of Wolf Point and Glasgow. However, there are no known drinking water wells producing from the Judith River near any injection wells located in the eastern half of the Reservation.

Considered as long
as compliance
with EPA Rules &
permits - i.e. no
EPA 8-D
policy or life limit

Although there is no current domestic use of the Judith River aquifer in the eastern half of the reservation, the UIC regulations still afford protection of aquifers which exhibit fewer than 10,000 mg/l TDS. Based upon this authority, EPA adopts the policy to prohibit new injection wells into the Judith River where it is defined as a USDW. By doing so, EPA recognizes the concerns of the Tribe that the Judith River Formation be preserved for future use.

POLICY
STATEMENT
NO. 2

It is concluded that the Judith River Formation in the Deadman's Coulee and Poplar Fields located to the east, is not now, nor was it prior to injection activities, a USDW. The Judith River is also confined from overlying USDWs by 800 to 1,000 feet of shale. The existing injection wells in these fields will be authorized to continue injecting into the Judith River Formation as long as compliance with appropriate EPA rules and permits is maintained. The following injection wells have pending permit applications:

60 in
60 days of
final approval
must be P&A

<u>EPA PERMIT</u>	<u>WELL NAME</u>	<u>FIELD</u>	<u>OPERATOR</u>
MTS21PR-0003	Goings No. 1	Poplar	Century Oil & Gas
MTS21PE-0009	Buck Elk No. 2	E. Poplar	Grace Petroleum
MTS21PE-0023	EPU 8-D	E. Poplar	Murphy Oil
MTS21PE-0024	EPU 29-D	E. Poplar	Murphy Oil
MTS21DM-0034	Allotted Hall	Deadman's Coulee	Reading & Bates

Discussion and Basis of Decision

Little water quality data are available for the Judith River Formation in the areas where most of the injection wells are located. However, a water analysis of a sample taken (prior to injection) from the Allotted Hall salt water disposal well, Deadman's Coulee Field, showed a TDS concentration greater than 10,000 mg/l. This sample was found to be reliable, based upon evaluation of the sampling technique. It is known that the formation downdips to the east and that TDS quality of the Judith River Formation increases from west to east. Therefore, the Judith River underlying the Poplar Field would also not qualify as a USDW.

Testimony presented by the Tribe asserted that injection fluids in the Poplar field may be forced to migrate updip and to the west (possibly to the far western edge of the Reservation) due to the fact that the Judith River Formation becomes pinched off by the Bearpaw Shale in the eastern portion of the Reservation. Pressure buildup effects, extending up to five miles, may influence the natural ground water flow pattern. However, from evaluation of the data, ground water flow reversal is not likely to exceed more than two miles from any wellbore.

A more significant impact than a reversal in ground water flow, is likely to be a flattening of the pressure gradient in the Judith River Formation. This may indirectly affect the residence time of the native fluids migrating west to east, thereby increasing the TDS concentration. However, it is not possible to estimate any direct impacts.

POLICY
STATEMENT
No. 3

Existing injection wells, in fields other than Deadman's Coulee and Poplar, will be allowed to continue injection activities so long as: 1) they maintain compliance with EPA rules and pending permit conditions, and 2) they do not inject more fluid than can be contained in that portion of the Judith River which has been exempted as a USDW. It is EPA's decision to limit injection in these fields to the existing 1/4-mile aquifer exemption radius. This will be done by limiting the life of individual injection wells through the permitting process.

The following wells have pending permit applications or operators have been requested to submit permit applications:

EPA PERMIT	WELL NAME	FIELD	OPERATOR
MTS21TC-0039	Lough No. 2	Tule Creek	Petro Lewis Corp.
MTS21TE-0035	Lillian 1-D	East Tule Creek	Murphy Oil
MTS21TC-0036	Sletvold	Tule Creek	Murphy Oil
MTS21LS-0038	Mann No. 1	Long Creek	Pennzoil
MTS21TC-0086	Phillips-McKee	Tule Creek	BHP Petroleum
	Wetsit No. 1	East Benrud	Murphy Oil
	Courchene 1-D	Volt	Murphy Oil
	Stai No. 1	East Benrud	Franks Petroleum D.C.

Discussion and Basis of Decision

Other fields where injection into the Judith River Formation is occurring are the Tule Creek, E. Tule Creek, Benrud, E. Benrud, Volt, and Long Creek. These fields lie west/northwest of the Deadman's Coulee and Poplar Fields and there is evidence that the Judith River Formation here may have contained fewer than 10,000 mg/l TDS before injection practices began.

The UIC regulations specifically prohibit injection into USDW's unless the aquifer is exempted. An aquifer exemption may be granted by EPA, and essentially allows injection into a formation which would otherwise be classified as a USDW but which is not likely to serve as a source of drinking water. All of the wells injecting into the Judith River Formation were granted aquifer exemptions for 1/4 mile radius from the wellbore at the inception of the UIC program in Montana on June 25, 1984. Notice of these aquifer exemptions was published in the FEDERAL REGISTER on September 2, 1983.

Don't inject to the well radius by limiting life of well

Using Judith River Formation characteristics and operating parameters for all the wells, calculations were done to determine the extent of formation fill-up from salt water disposal practices. These calculations are an estimate of how far the injection fluids have traveled from each wellbore. A factor of 25 percent was used in the calculations to safely accomodate uncertainty and pore volume inaccessibility to injected fluids.

In certain instances, injection wells have already surpassed the fill-up volume allowed by their authorized 1/4-mile aquifer exemptions. Permits for these wells will be denied and the operator will be required to properly plug and abandon the wells.

FOR MORE INFORMATION

EPA's technical evaluation report, the transcript of the hearing, and other pertinent documents, are available for inspection at the following locations:

Environmental Protection Agency
Region VIII
Drinking Water Branch 8WM-DW
One Denver Place, Suite 1300
999-18th Street
Denver, Colorado 80202-2413
Telephone: (303) 293-1415

Environmental Protection Agency
Montana Office
Federal Office Building
Drawer 10096
301 South Park
Helena, Montana 59626
Telephone: (406) 449-5486

TECHNICAL EVALUATION

Review of Data Relating to Injection of Oil Field Brines
in the Area of the Fort Peck Indian Reservation

Prepared by: Paul S. Osborne
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The U.S. Environmental Protection Agency (EPA or Agency) received a request from the tribal government of the Fort Peck Indian Reservation to prohibit further injections into the Judith River Formation (Fm.). The Tribe alleged that continued injection would affect the quality of water in the Judith River Fm. such that its use for irrigation purposes on the western part of the Reservation would be jeopardized. A public hearing was held in Poplar, Montana on May 29, 1985, to collect information relating to existing injection into the Judith River Fm.

A review of the available data (attached as appendices) pertaining to Judith River Fm. injection activities has been completed. Figure 1 shows the Fort Peck Indian Reservation and the fields which are the concern of this analysis.

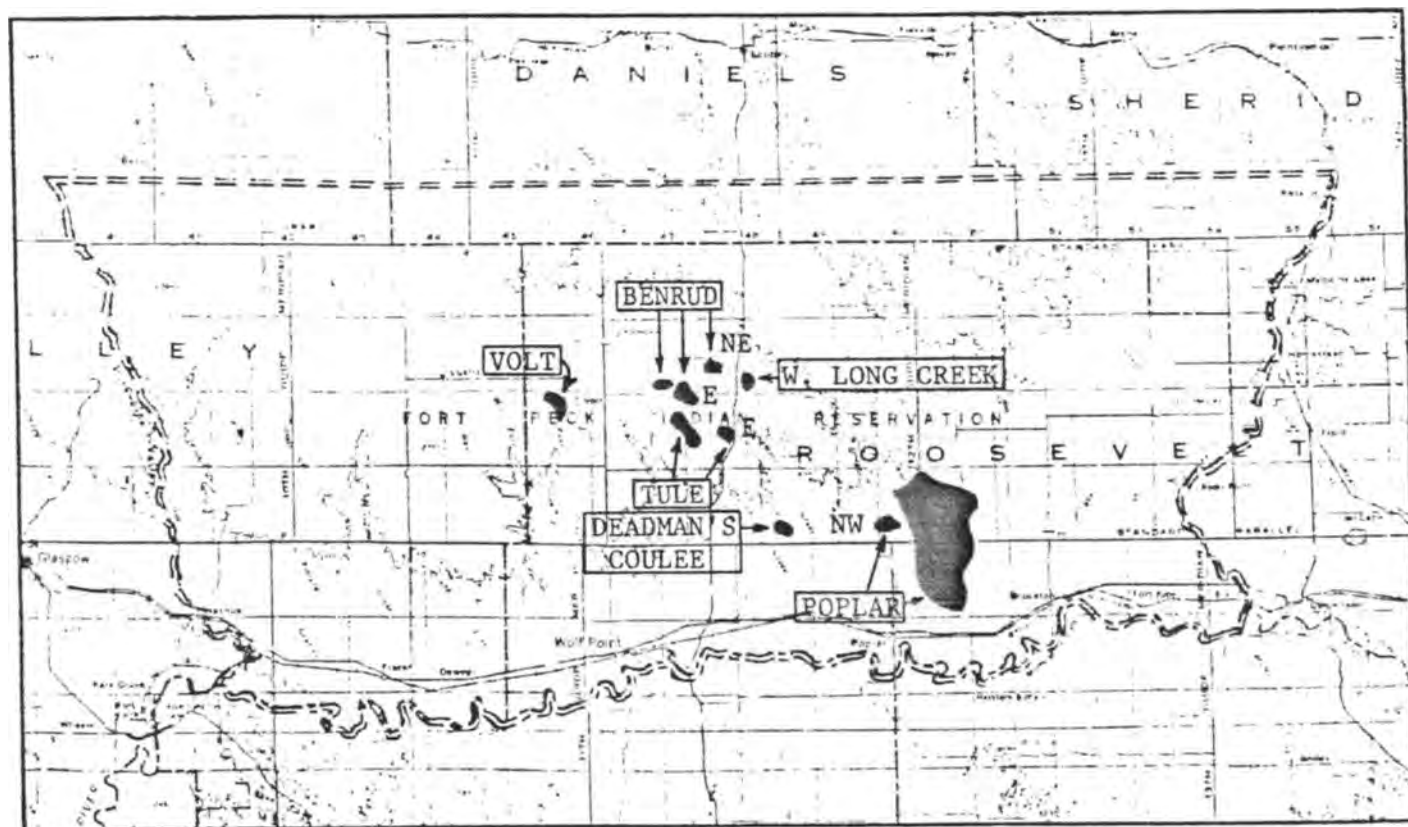


FIGURE 1. Approximate Field Locations - Fort Peck Reservation, Montana.

The data reviewed were related to the Judith River Fm. from west of Glasgow, Montana to the eastern edge of the Reservation. The review included an inspection of several wells in the Poplar, Volt, Tule, and Benrud Fields located within the Fort Peck Reservation. The questions to be addressed by this report are the following:

1. Are the aquifer exemptions of 1/4 mile radii granted at the inception of the Underground Injection Control (UIC) program, adequate for the volumes of fluids injected?
2. What is the ambient quality of the Judith River Fm. over the entire Reservation?
3. Is the Judith River Fm. sufficiently confined to prevent contamination of overlying underground sources of drinking water (USDW's)?
4. Is fluid migration (east to west) a real possibility given that the Judith River Fm. is "pinched off" by the Bearpaw Shale on the eastern edge of the Reservation?
5. What alternative drinking water sources are there on the Reservation? Are data available so that an equal concentration (total dissolved solids (TDS)) contour map can be constructed (i.e., greater than 10,000 milligrams/liter (mg/l); less than 10,000 mg/l for other sources of drinking water)?

Conclusions relating to these issues are summarized in the following section. This is followed by a section of detailed discussions of each issue.

SUMMARY AND CONCLUSIONS

This information and other available data were used in formulating the following conclusions.

1. Using the radius-of-formation-fillup and travel-time formulas (both based on radial flow), it appears that four existing wells have exceeded or will soon exceed their 1/4-mile aquifer exemptions. In fact, one well has probably directly impacted the reservoir up to a distance of one half mile from the well. Any permits should be evaluated to determine if the 1/4 mile radius of exempted aquifer is adequate.

2. It is not possible to draw TDS contours of the ambient water quality for the Judith River Fm. over the entire Reservation. There is very little reliable data on which a contour map could be based. Data from water wells on the west side of the Reservation; a water well at Wolf Point; and a drill stem test, indicate that TDS concentrations increase from east to west. These data indicate that the Judith River Fm. was a USDW in the vicinity of the Tule Field; TDS values in the Poplar Field were always in excess of 10,000 mg/l.
3. Based on composition, thickness, and apparent low permeability of the Bearpaw Shale Fm., it appears that the Judith River Fm. is sufficiently confined to prevent fluid contamination of overlying USDW's.
4. Estimates of the radius-of-fillup indicate that even with dispersion, the direct impact of the injected water will be limited to less than a 1/2 mile for any given injection well reviewed. This will create a limited amount of east to west fluid migration due to the mounding effect caused by the injection and subsequent displacement of existing reservoir water back to the west.
5. The INDIRECT impacts of injection into the Judith River Fm. in the Poplar Field could have a significant impact to the west because of the large pressure buildup in the field since injection was initiated. Fluid pressure buildup estimates indicate that significant pressure effects could extend beyond a five mile radius. While this may not result in westward fluid migration as far as five miles, it will result in a flattening of the preinjection gradient. This will result in increased travel times of native water moving west to east, which should result in an increase in TDS.
6. Calculations using the existing injection pressures, obtained from data supplied by Larry Monson, indicate that all but seven of the 17 current and standby injection wells are operating at pressures which exceed a fracture gradient of 0.75 pounds per square inch (psi/ft).
7. The principal sources of drinking water in the vicinity of the oil fields, where injection into the Judith River Fm. is occurring, are the alluvium and glacial gravels. There are also several areas which receive supplies from bedrock aquifers of limited areal extent, such as the Fox Hills. There is insufficient data to draw either TDS contours or the extent of the aquifers in question.

8. Available data indicate that the Judith River Fm. in the vicinity of the Volt and Tule Fields was a USDW prior to injection activities. Continued injection in these fields will increase the size of the presently impacted area, therefore, limiting injection to the existing 1/4 mile aquifer exemption should be considered when establishing the expiration dates of the permits. Continued injection in the Poplar Field may have little impact on the aquifer to the west of the field, but there may be some indirect impact caused by a flattening of the gradient between the Poplar Field and the various fields to the west.

DISCUSSION

1. Are the 1/4 mile aquifer exemptions for the given injection wells, granted at the inception of the UIC program, adequate for the volumes of fluids injected?

There are several methods which can be used to estimate the extent of movement of injected fluids away from a well. It is possible to calculate the time for fluid to move from an injection well to a point which is a given distance, r , away. The formula, derived by integrating the equation for the average velocity through porous material, is given as:

$$t = \frac{\pi \phi b r^2}{Q}$$

Where:

- ϕ = porosity of reservoir
- b = thickness of reservoir (ft)
- r = distance from injection well (ft)
- Q = injection rate (ft³/day)
- t = travel time (days)

This equation assumes the following:

- a. flow from the well is radial;
- b. the reservoir thickness is uniform;
- c. the effect of the regional flow gradient on the plume is negligible;
- d. the porosity is uniform; and
- e. there are no dispersion effects.

The primary variables in calculating travel time are porosity and thickness of the formation. In the case of the Judith River Fm., the porosity varies from 10% to 20%, (Feltis, 1982).

A compensated neutron and formation density log was available for the Goings 27-3 in Section 27, T29N, R50E. This log indicated an average porosity of about 16.5%. Other experts with knowledge of the Judith River Fm., however, indicate that a porosity of less than 15% should be expected in much of the formation (Marvin Miller, Personal Communication).

The thicknesses of the sand units in the Judith River Fm. underlying the Reservation are quite variable, ranging from less than 10 feet to about 125 feet. The sandstone generally occurs in two discrete units which are separated by claystones. Analysis of a map showing cumulative thickness of sandstone in the Judith River Fm. (prepared by Larry Monson, Fort Peck Mineral Resources) indicates a thinner sandstone layer between the Benrud-Tule Creek Fields and the Poplar Field. Spatial changes in sandstone thickness within each of the given fields, however, is small enough to base travel-time estimates on the sand thickness encountered at each individual well. For purposes of these calculations, sand thickness was estimated using the total sum of the perforated intervals. The estimates correlate well with the map of Judith River Fm. sand thickness. In most cases the perforated intervals encompass all the available sand.

Table 1 shows the travel times assuming three different porosities, 10%, 16.5%, and 20%. The injection rates were estimated using the total volume injected since injection started in each of the wells. This assumes that the injection rate was continuous and constant. The radii of interest are 1/4 mile (1,320') and 1/2 mile (2,640'). A 1,000 foot radius was used for the calculations, instead of 1,320 feet, to allow a margin of safety. As indicated, the travel time increases rapidly as the radius increases. Travel time is also influenced by the direct relationship with porosity; doubling of porosity will double the travel time.

The analysis indicates that even if porosity in some of the reservoir approaches 20%, fluids from several wells will have traveled close to or greater than 1/4 of a mile (1,320 feet) after 15 years of injection (5,475 days). The wells in question are the Courchene 1-D, the Sletvold B1, the Allotted Hall SWD, the Goings 1, the Reynolds EPU 8, the Bierre 1 (plugged in 1984), the Buck Elk 2, and the EPU 29-D. Of these wells, the Courchene 1-D, the Sletvold B1, and the Buck Elk 2 have already injected for at least 15 years.

An alternative means of estimating the impact of injected fluids upon a reservoir is to calculate the "radius of fillup." This value can be used to calculate the size of the cylinder of reservoir rock to be filled by the total injected fluid volume. The equation to calculate this radius is given as:

$$r_f = \frac{(W) 5.615}{(\pi)(b)(\phi)}$$

Where:

r_f = radius of fillup (ft);
 W = total injected volume (barrels);
 ϕ = porosity;
 b = sand thickness (ft); and
 5.615 = conversion factor (ft³/bbl)

TABLE 1. TRAVEL TIME FROM INJECTION WELL TO A GIVEN POINT, R

LOCATION	WELL NAME	VOLUME INJECTED PER DAY (ft ³ /day)	TRAVEL TIME (days)					
			R = 1,000 feet			R = 2,640 feet <i>1/2 mi radius</i>		
			$\phi = .1$	$\phi = .165$	$\phi = .20$	$\phi = .1$	$\phi = .165$	$\phi = .20$
SE SW 4-30-46	Courcne 1-D	7,300	2,366	3,904	4,732	16,488	27,206	32,976
NW NE 9-30-46	Carlson	1,291	7,297	23,039	14,594	50,855		
SE NE 13-30-47	Phillips-McKee	5,351	4,108	6,772	8,216	28,629		57,258
C SE SW 13-30-47	Lough 2	3,099	4,762	7,857	9,524	33,190		
NE NE SW 34-31-47	A 1-W Listug-Olson							
SW NE SW 36-31-47	Wetsit 1	3,296	6,288	10,375	12,576	43,822		87,644
NW NE 6-30-48	Bigtrack Little 1	1,259	4,988	8,230	9,976	34,765		
NW SE NE 15-30-48	Bridges 1-D	1,959	9,617	15,868	19,234	67,028		
C NW NE 19-30-48	Sletvold B1	3,694	2,550	4,208	5,100	17,773	29,325	35,546
SW SE 20-31-48	Mule Creek 1-D	1,583	27,770	45,821	55,540	193,546		
SE NE 25-31-48	Mann 1 SWD	1,645	19,470	32,125	38,940	135,697		
NW NE 29-29-49	Allotted Hall SWD	12,576	998	1,647	1,996	6,064	11,486	13,922
NE NW 27-29-50	Goings 1	6,086	2,270	3,745	4,540	15,822		31,644
SE NW NE 10-28-51	Huber 1-W	3,116	14,712	24,274	29,424	102,540		
NW SE 10-28-51	Reynolds EPU 8-D	35,107	447	738	894	3,117	5,143	6,234
SW NW SW 22-28-51	Bierre 1	5,266	1,442	2,379	2,884	9,974	16,457	19,948
SW NW 7-29-51	Buck Elk 1	3,722						
SW NW 7-29-51	Buck Elk 2	2,790	2,250	3,712	4,500	15,688		
SW SW 28-29-51	EPU 29-D	11,409	935	1,543	1,870	6,522	10,761	13,044
SW SW SW 31-31-48	Stai 1 SWD	455	35,886	59,212	71,772	250,109		

$$\frac{5743}{365} = 14 \text{ yrs.}$$

The use of this equation assumes that:

- a. flow is radial;
- b. reservoir thickness is constant;
- c. existing flow gradient does not affect plume movement; and
- d. there are no dispersion effects.

This equation is sensitive to both the change in volume and the change in porosity. The porosity is most important in that an increase in porosity will cause a decrease in the radius of impact. Using a high value for porosity will provide a sense of the minimum size of the area of impact. The results that appear in Table 2 were obtained by assuming a porosity of 15% and no dispersion.

As is indicated by the results, injection in several wells has been of sufficient quantity to cause the 1/4 of a mile radius to be exceeded. These wells are the Courchene 1-D, the Sletvold B1, the Reynolds EPU-8, the Bierre 1 (plugged), and the Buck Elk 2. Well EPU 29-D will exceed the 1/4 mile radius within a year.

As mentioned previously, the radius of fillup equation does not take into account dispersion. The dispersion mechanism can cause the plume of injected water to be significantly larger than a plume with no dispersion. The dispersion effect can be estimated using an equation developed by Bear (1972), which is given by:

$$r' = r + 2.3 \sqrt{(D)(r)}$$

Where:

- r' = radial distance of contaminant movement with dispersion (ft);
- r = calculated radius of fillup with no dispersion (ft);
- D = dispersion coefficient (ft).

This equation estimates the point at which the injection front possesses a chemical concentration of 0.2% of the injected fluid. The dispersion coefficient varies according to the composition of the aquifer. Experiments indicate a dispersion coefficient of three feet for sandstone while the value for a vuggy limestone would be 65 feet.

Table 3 shows the calculated radius of fillup with and without dispersion, assuming a higher porosity of 20%. The increase in porosity of 5% does not affect the radius of fillup estimates shown in Table 2, by more than 150 feet. Table 3 also shows calculations of the radius of the injected front using Bear's dispersion equation. The dispersion coefficient was assumed to be 3 feet. The results of the calculations further support the data on Tables 1 and 2, which indicate that several wells already have plumes in excess of 1/4 mile, even when assuming a high value for porosity.

TABLE 2. RADIUS OF FILL-UP OF JUDITH RIVER INJECTION WELLS
FORT PECK INDIAN RESERVATION

LOCATION	NAME	FIELD	TOTAL VOLUME INJECTED (bbls)	TIME SINCE START UP (days)	RADIUS* OF FILL-UP (feet)	SAND THICKNESS (feet)
SE SW 4-30-46	Courchene 1-D	Volt	9,490,953	7,300		
NW NE 9-30-46	Carlson	Volt	837,942	3,650	577	30
SE NE 13-30-47	Phillips-McKee	Tule	1,391,601	1,460	987	70
C SE SW 13-30-47	Lough 2	Tule	3,830,468	6,935	986	47
NE NE SW 34-31-47	A 1-W Listug-Olson	Benrud	642,238		330	70
SW NE SW 36-31-47	Wetsit 1	E. Benrud	4,074,613	6,935	585	66
NW NE 6-30-48	Bigtrack Little 1	E. Benrud	980,047	4,380	764	20
NW SE NE 15-30-48	Bridges 1-D	E. Tule	2,164,863	6,205	656	60
C NW NE 19-30-48	Sletvold B1	Tule	6,005,777	9,125	1,544 (29 mi)	30
SW SE 20-31-48	Mule Creek 1-D	N.E. Benrud	2,164,863	7,665	429	140
SE NE 25-31-48	Mann 1 SWD	W. Long Creek	641,248	2,190	273	102
NW NE 29-29-49	Allotted Hall SWD	Deadman's Coulee	2,452,707	1,095	854	40
NE NW 27-29-50	Goings 1	N.W. Poplar	1,186,616	1,095	567	44
SE NW NE 10-28-51	Huber 1-W	Poplar	5,068,610	9,125	643	146
NW SE 10-28-51	Reynolds EPU 8	Poplar	15,975,426	2,555	1,952 (37 mi)	50
SW NW SW 22-28-51	Bierre 1	Poplar	4,795,534	5,110	1,543	24
SW NW 7-29-51	Buck Elk 1	Poplar	1,210,118	1,825		
SW NW 7-29-51	Buck Elk 2	Poplar	3,263,920	6,570	1,394	20
SW SW 28-29-51	EPU 29-D	Poplar	3,709,121	1,825	1,140	34
SW SW SW 31-31-48	Stai 1 SWD	E. Benrud	448,204	5,475	428	52

* Radius of fill-up calculations assume a porosity of 15%.

1/4 mi = '320'

TABLE 3. RADIAL DISTANCE OF INJECTION FRONT
WITH AND WITHOUT DISPERSION

LOCATION	WELL NAME	SAND THICKNESS (feet)	TOTAL VOLUME INJECTED (bbls)	RADIUS OF FILL-UP * (feet)	
				WITHOUT DISPERSION	WITH DISPERSION
SE SW 4-30-46	Courchene 1-D	59	9,490,953	1,242	1,382
NW NE 9-30-46	Carlson	30	837,942	499	587
SE NE 13-30-47	Phillips-McKee	70	1,391,601	421	502
C SE SW 13-30-47	Lough 2	47	3,830,468	853	969
NE NE SW 34-31-47	A 1-W Listug-Olson	70	642,238	286	353
SW NE SW 36-31-47	Wetsit 1	66	4,074,613	742	850
NW NE 6-30-48	Bigtrack Little 1	20	980,047	661	763
NW SE NE 15-30-48	Bridges 1-D	60	2,164,863	567	662
C NW NE 19-30-48	Sletvold B1	30	6,005,777	1,338	1,483
SW SE 20-31-48	Mule Creek 1-D	140	2,164,863	371	447
SE NE 25-31-48	Mann 1 SWD	102	641,248	237	298
NW NE 29-29-49	Allotted Hall SWD	40	2,452,707	740	848
NE NW 27-29-50	Goings 1	44	1,186,616	491	579
SE NW NE 10-28-51	Huber 1-W	146	5,068,610	557	651
NW SE 10-28-51	Reynolds EPU 8	50	15,975,426	1,690	1,853
SW NW SW 22-28-51	Bierre 1 <i>REA</i>	24	4,795,534	1,336	1,482
SW NW 7-29-51	Buck Elk 1		1,210,118		
SW NW 7-29-51	Buck Elk 2	20	3,263,920	1,208	1,346
SW SW 28-29-51	EPU 29-D	34	3,709,121	988	1,113
SW SW SW 31-31-48	Stai 1 SWD	52	448,204	277	343

* Radius of fill-up calculations assume a porosity of 20%.

Based on the analysis of the data, it is clear that the exempted areas are not sufficient in portions of the aquifer where injection is occurring and the TDS is less than 10,000 mg/l. Given the fact that flow will not be radial because of geologic structure, fluid density differences, and existing gradient, the impacted area of aquifer may be at least 1/2 mile. Based on calculations performed during this review, there are four operating wells which impact an area of the aquifer larger than 1/4 mile and which may need a slightly larger exemption (if an exemption is required), because of the large volume of fluids already injected. The wells in question are EPU 29-D, Reynolds EPU-8, Allotted Hall SWD, and Courchene 1-D.

In summary, there are wells in the Poplar Field which have injected sufficient quantities of water to impact reservoir water beyond the 1/4 of a mile radius. Additionally, a well in the Volt Field and a well in Deadman's Coulee Field have exceeded the 1/4 mile radius. When these four wells are permitted, any exemption deemed necessary should be for a minimum of 1/2 mile to a mile. Any other wells which are permitted should be evaluated using radius of fillup calculations for the proposed life of the well, in order to estimate the size of impacted area. (S)

2. What is the ambient quality of the Judith River Fm. over the entire Reservation?

The Judith River Fm. consists of approximately 500 feet of grayish-white sandstone and light to dark gray sandy shale and clay. Locally, beds of coal and carbonaceous shale occur, such as that encountered in wells on the western edge of the Reservation near Glasgow, Montana. Individual beds of sandstone or shale are not always continuous either in thickness or character, and consequently the sequence of alternating types of rock differs laterally.

The number of sandstone beds and the distance of such beds below the top of the Judith River Fm., are not the same in all localities. Generally, there are two major sandstone layers in the Judith River Fm. on the west side of the Reservation. The Judith River Fm. (400 to 100 feet thick on the Reservation) thins from west to east. The sand layers inter-tongue from east to west and only one layer is present in the Poplar Field area. The Judith River Fm. outcrops west of the Reservation and plunges to the east. There is also a steep plunge to the southeast off the Poplar Dome.

There is a limited amount of data on the water quality and the hydrology of the Judith River Fm. Based on the structural geology of the Fort Peck area and the location of the outcrop of the Judith River Fm., the direction of ground-water flow is most likely from the west to the east and southeast. Water quality data indicate an increase in TDS from west to east. Although Judith River Fm. water quality is marginal for drinking, it is used in the western portion of the Reservation for livestock purposes. Table 4 gives the location of wells for which TDS information is available. As indicated, the TDS ranges from less than 2,000 mg/l in a well in T34N, R40E, to more than 18,000 mg/l in a well in T29N, R51E.

Table 4. Total Dissolved Solids Content for
Samples from the Judith River Formation.

LOCATION	TOTAL DEPTH (ft.)	SAMPLE DATE	TDS (mg/liter)	REMARKS
Sec. 6 T27N,R40E	495	1978	2802	
Sec. 31 T28N,R40E	555	1978	2126	
Sec. 11 T34N,R40E	405	1982	1444	
Sec. 31 T36N,R40E	1700	1971	2303	
Sec. 14 T26N,R41E	936	1947	2419	
Sec. 2 T27N,R41E	695	1978	2724	
Sec. 30 T28N,R41E	454	1978	2851	
Sec. 35 T28N,R41E	685	1978	2765	
Sec. 34 T27N,R44E	1090	1947	4133	
Sec. 15 T27N,R47E	985	1947	3862	
Sec. 22 T27N,R47E	1100	1947	3552	City of Wolf Point
Sec. 15 T30N,R48E	1411	1964	15,602	DST *
Sec. 13 T28N,R50E	874	1954	11,475	DST
Sec. 19 T29N,R51E	877	1957	18,624	DST *
Sec. 15 T30N,R49E	1600	1964	16,653	DST *
Sec. 24 T36N,R52E	1940	1957	10,385	DST
Sec. 4 T30N,R46E	1432	1965	15,056	*
Sec. 29 T29N,R49E	1270	1982	11,323	DST

* Sampling methods were questionable and therefore, analytical results are considered invalid for purposes of this review.

As can be seen in the values of TDS, there is a great deal of variation within given areas. This may reflect poor "quality assurance" in either the sampling or analysis. This is especially true of the data obtained by drill stem tests. For instance, the sample from the Courchene 1-D had a calculated TDS of about 15,000 mg/l. The sample was muddy, indicating that some contamination may have been present. Additionally, this sample does not compare with the data from the wells at Wolf Point, which have TDS values of less than 4,000 mg/l.

The Wolf Point wells are about six miles east and 15 miles south of the Courchene 1-D well in the Tule Field. Given the apparent west to east flow, it is difficult to postulate why the quality would have so much variability in a north-south direction.

For purposes of this report, most of the data obtained from DST samples were considered to be questionable, except where documentation indicated a valid sample. The valid data verify that quality does change from west to east. The TDS information obtained from the samples in T28 and 29N, R48, 49, and 51E do not correlate with the samples taken on T26N, R52E, and T29N, R49E. This may be related to sampling error. The sample taken in T36N, R52E had sufficient documentation to show that it was representative of the Judith River Fm.

Ignoring the samples that are questionable, it can be intimated that the TDS increases from about 4,000 mg/l in T27N, R47E to about 11,000 mg/l in T28N, R50E (a distance of 10 to 15 miles). Water quality data from the Poplar Field support a finding that the TDS has always been in excess of 10,000 mg/l.

Data from several electric logs were used to estimate the TDS in several oil wells drilled in various parts of the Reservation. These estimates were made using Archie's law:

$$R_w = R_o/F$$

Where:

- R_w = resistivity of the formation water;
- R_o = resistivity of the formation including the water it contains obtained from log);
- F = Formation factor which depends on the porosity and other characteristics of the unit.

The Formation Factor is an empirical constant which depends on such formation characteristics as porosity. The Judith River Formation Factor was estimated using the electric log and the actual value of TDS from the Allotted Hall #1 SWD well in Section 29, T29N, R49E. The calculations are as follow:

$$\begin{aligned} R_w \text{ (at } 168^{\circ}\text{F)} &= 0.24 \text{ (from Welex charts on salinity)} \\ \text{BHT} &= 168^{\circ}\text{F} \\ \text{TDS} &= 11,000 \text{ mg/l} \\ R_o &= 3.0 \text{ ohm-m (from log)} \\ F &= R_o/R_w = 3.0/0.24 \\ F &= 12.5 \end{aligned}$$

The Formation Factor was assumed to be constant and Archie's Law was used to estimate the TDS content of the Judith River Fm. in several locations where R_o values of the formation could be obtained from well logs. Estimates were made for several locations along an east-west line where electric logs run on production wells were available. Table 5 gives the information from the logs and the resulting estimates of TDS.

Table 5. Estimates of TDS Using Resistivity						
NAME	LOCATION	BHT	R ₀	R _w	TDS	
#1 Gess	Sec. 1 T30NR463	179°F	10.1	0.81	3000	
#1 Rodger	Sec. 15 T31NR42E	158°F	6.5	0.52	5300	
Franz #1	Sec. 30 T31NR45E	140°F	15	1.2	2500	
C. Reddig #2	Sec. 30 T31NR44E	165°F	6	0.48	5500	
C. Reddig #2		165°F	8.5*	0.68	3800	
#1-7 Bectman	Sec. 7 T30NR46E	155°F	7.5	0.6	4400	
Clark #1-MA	Sec. 4 T29NR49E	168°F	3.0	0.28	9500	

* Note: It was not possible to determine which track on the log was the actual R₀ value. The 2nd track had a large value of R.

These estimates indicate that the TDS content from wells west of the Poplar Field is less than 10,000 mg/l. This information provides some support to the data from the well in Wolf Point (Section 22, T27N, R47E), which has a TDS of about 3,500 mg/l. This would indicate that a gradual increase in TDS occurs as water moves from west to east, such that wells about 16 miles to the northeast have a TDS in excess of 10,000 mg/l. It is important to note, however, that calculations using the Formation Factor are questionable at best because of the lack of reliable quality data and good electric logs.

In summary, existing data indicate that the Judith River Fm. is a USDW on the western edge of the Reservation. The TDS concentration of the water in the formation increases towards the east such that the aquifer is not a USDW in the Poplar Field. Data from the Allotted Hall SWD well in Deadman's Coulee Field (supported by documentation indicating that the sample was representative) indicate that the portion of the Judith River Fm. in this area was not a USDW prior to any injection. There is insufficient data available to delineate the actual boundary of the USDW, but it is possible to state that the Poplar Field is not now, and has probably never been, a USDW. The Judith River Fm. underlying the Volt, Tule, and Benrud Fields however, may have been a USDW prior to injection.

3. Is the Judith River Fm. sufficiently confined to prevent contamination of overlying USDW's?

The Judith River Fm. on the Fort Peck Reservation is overlain by the Bearpaw Shale, which also dips from west to east. The western margin of the Bearpaw is located west of Glasgow, Montana. The depth to the Judith River Fm. on the Reservation ranges from about 500 to about 1,300 feet. This depth

to the Judith River Fm. is dependent on the geologic structure and the surface topography. The Judith River Fm. is at shallow depths in the East Poplar Field because of the Poplar Dome and the presence of the Poplar River Valley. Generally, however, the Judith River Fm. is shallowest on the western edge of the Reservation.

The Bearpaw Shale is a gray marine shale, sandy in the upper portions, and is gradational with the overlying Fox Hills Sandstone. The total thickness of the Bearpaw is about 1,200 feet. The shale is tight except in the upper part or in places where it has been deeply weathered, and it generally will not yield water to a well. Any water that might be obtained from permeable zones in the shale probably would be too highly mineralized for domestic or stock use. This is evidenced by the presence of numerous saline seeps (associated with the fallowing practices used in some dry/land farming). Water from saline seeps has been found to have a total dissolved solids content ranging from 5,000 to 70,000 mg/l.

Available well data indicate that the Judith River Fm. is under confined conditions such that wells flow at the surface. For instance, two wells located near Wolf Point were under flowing conditions in 1947. Surface pressures measured in the Poplar and Tule Fields are as high as 900 psi. While much of this pressure is in response to the existing injection activity, initial shut-in pressures indicate that even without injection, wells in the oil fields would probably flow at the surface.

The reported injection pressures for wells injecting into the Judith River Fm. (Larry Monson, Fort Peck Mineral Resources), were used to calculate the present injection gradient for each well. These calculations indicate that all but 7 of the 17 current and standby injection wells are operating at pressures which could exceed a fracture gradient of 0.75 psi/ft. Five wells are injecting at pressures in excess of 1.0 psi/ft. These are the Lough #2, the Allotted Hall SWD, the Goings #1, the Reynolds EPU-8, and the EPU 29-D. The Reynolds EPU-8 is injecting at the highest gradient (1.27 psi/ft).

No data on actual fracture pressure of the Judith River Fm. is apparently available. Although one operator indicated that the fracture gradient was 1.25 psi/ft, no documentation was provided to verify this claim. It is unlikely that the fracture gradient of the Judith River Fm. exceeds 0.8 psi/ft based on data from other reservoirs with similar characteristics. Even if the reservoir is fractured, the overlying shales may be of sufficient thickness to prevent fractures such that fluid will not migrate into USDW's overlying the 800 to 1,000 feet of shale. Field studies have shown that injection energy dissipates rather quickly once the fractures move out of the reservoir. The fracturing of the reservoir on the other hand could present a problem. It will provide discreet zones of high permeability which will provide avenues for injected fluid to move further from the well than estimated by the radial flow calculations. Additional data obtained from valid step rate tests should be used to justify injection pressures over 0.8 psi/ft.

Based on the thickness and low permeability of the Bearpaw Shale, combined with the evidence that the Judith River Fm. is under confined conditions, it appears that the Bearpaw Shale is adequate to prevent movement out of the injection zone. This may depend however, on the actual fracture gradient of the Judith River Fm. and the Bearpaw Shale. Although injection activities will have some impact on the pre-injection flow patterns of the Judith River Fm., there is inadequate data to develop a map to show these actual flow patterns. In order to develop such a map, it would be necessary to shut in all of the injection wells and measure the shut-in pressure.

4. Is fluid migration (east to west) a real possibility given that the Judith River Formation is pinched off by the Bearpaw Shale on the eastern edge of the Reservation?

As discussed previously, the Judith River Fm. dips from west to east towards the Williston Basin. This formation outcrops at the surface near the Milk River, West of Glasgow and is considered to be a significant location for recharge to the Judith River Fm. The pre-injection flow pattern was probably west to east, with a southern component of flow, especially in the Poplar Dome area.

The dip of the Judith River Fm. increases east of the Dome due to the presence of the Williston Basin, which is a deep synclinal trough.

Available logs and cross sections indicate that the depth of the Judith River Fm. increases by 900 feet between a well in Section 29, T29N, R50E and a well in Section 35, T29N, R52E, which is a distance of about 10 miles.

The sand units in the Judith River Fm. also thin from thicknesses of about 80 feet to about 10 feet. Some experts have indicated (Larry Monson, personal conversation, 1985) that the sand unit is not present further out in the Williston Basin. A well in Section 28, T29W, R55E, however, shows a Judith River Fm. sand thickness of about 100 feet. Based on this data it is clear that the Judith River has definable sandstone layers present well out into the basin. It is not possible without looking at well logs from holes in North Dakota, to speculate on the full extent of the Judith River Fm. and its discharge zones.

Data on the permeability and porosity of the Judith River Fm. sandstone is not readily available but Feltis indicated that a porosity of 10 to 20% and a permeability of 25 millidarcies (md) was reasonable. Marvin Miller, of the Montana Bureau of Mines, indicated that an analysis of limited DST data indicated a range of permeabilities from 55 md to 109 md. This data can be used to estimate the pressure buildup at a given radius from injection using the following equation:

$$P_r = P_i + (70.6) \frac{(Q)(U)(B)}{(k)(b)} \left[E \left(\frac{39.5 (\phi)(U)(c)(r^2)}{(k)(t)} \right) \right]$$

where:

- P_r = Pressure at a given radius (psi);
- P_i = Initial pressure (psi);
- Q = Constant injection rate (barrels/day);
- B = Formation volume factor = 1;
- c = compressibility (psi^{-1}) = 7.5×10^{-6} ;
- U = viscosity (cp) = 1;
- k = permeability (md);
- b = thickness of reservoir (ft)
- ϕ = porosity
- E = Exponential integral

For purposes of this evaluation of pressure buildup, the following is assumed:

- a. flow is radial;
- b. the initial pressure is zero;
- c. well interference is not taken into account;
- d. porosity and thickness are constant;
- e. the well is fully penetrating;
- f. the radius of the injection well is assumed to be 0.5 ft.; and
- g. the injection rate is estimated using the total volume injected since a given well began operation and assumes the rate was constant.

Table 6 gives the estimated pressure buildup at the injection wells assuming a permeability of 25 md and a porosity of 15%. The table also lists the reported well head pressures. As indicated in the table, the calculated values of pressure buildup lie on both sides of the reported values. Generally, the calculated values were not greatly divergent from reported values.

The results provide a qualitative measure of the possible variations of permeability. The largest divergence was in the EPU-8 well and the Allotted Hall SWD well. This divergence may be caused by a higher permeability value than was assumed; a larger thickness of reservoir than assumed; or an over estimation of the volume disposed.

Table 7 lists estimates of pressure buildup at the well and at a radius of 5 miles, assuming permeabilities of 55 md and 109 md. The pressure buildups at the wells are more realistic than those estimated assuming a permeability of 25 md. This is especially true in light of the fact that there was an initial positive formation pressure in the field, which was assumed to be zero for purposes of these calculations. The important point of these estimates is that all wells are causing significant pressure increases at a distance of five miles.

TABLE 6. PRESSURE BUILDUP ESTIMATE FOR JUDITH RIVER INJECTION WELLS
FORT PECK INDIAN RESERVATION

LOCATION	WELL NAME	FIELD	DAYS SINCE INITIAL INJECTION BEGAN	VOLUME * INJECTED PER DAY (bbls)	PRESSURE BUILDUP ** AT WELL (psi)	REPORTED PRESSURE (psi)
SE SW 4-30-46	Courchene 1-D	Volt	7,300	1,300	0	470
NW NE 9-30-46	Carlson	Volt	3,650	230	482	400
SE NE 13-30-47	Phillips-McKee	Tule	1,460	953	820	478
C SE SW 13-30-47	Lough 2	Tule	6,935	552	552	759
NE NE SW 34-31-47	A 1-W Listug-Olson	Benrud				350
SW NE SW 36-31-47	Wetsit 1	E. Benrud	6,935	587	575	700
NW NE 6-30-48	Bigtrack Little 1	E. Benrud	4,380	224	709	400
NW SE NE 15-30-48	Bridges 1-D	E. Tule	6,205	349	374	WR
C NW NE 19-30-48	Sletvold B1	Tule	9,125	658	1,435	800
SW SE 20-31-48	Mule Creek 1-D	N.E.	7,665	282	131	630
SE NE 25-31-48	Mann 1 SWD	W. Long	2,190	293	176	300
NW NE 29-29-49	Allotted Hall SWD	Deadman's Coulee	1,095	2,240	3,327	900
NE NW 27-29-50	Goings 1	N.W. Poplar	1,095	1,084	1,465	750
SE NW NE 10-28-51	Huber 1-W	Poplar	9,125	555	249	400
NW SE 10-28-51	Reynolds EPU 8-5	Poplar	2,555	6,253	7,727	700
SW NW SW 22-28-51	Bierre 1	Poplar	5,110	938	2,494	400
SW NW 7-29-51	Buck Elk 1	Poplar	1,825	663		400
SW NW 7-29-51	Buck Elk 2	Poplar	6,570	497	1,602	400
SW SW 28-29-51	EPU 29-D	Poplar	1,825	2,032	3,640	650
SW SW SW 31-31-48	Stai 1 SWD	E. Benrud				

* Injection volume per day estimates based on assumption that injection has been continuous.

** Calculations of pressure buildup at the well are based on assumption of permeability of 25 millidarcies and porosity of 15%.

TABLE 7. PRESSURE BUILDUP AT A GIVEN DISTANCE, R

TABLE 7. PRESSURE BUILDUP AT A GIVEN DISTANCE, R								
LOCATION	WELL NAME	FIELD	DAYS SINCE INITIAL INJECTION BEGAN	ESTIMATED PRESSURE BUILDUP * (psi)				SAND THICKNESS
				permeability = 55 md		permeability = 109 md		
				R=0.5 ft	R=5 miles	R=0.5 ft	R=5 miles	
SE SW 4-30-46	Courchene 1-D	Volt	7,300					
NW NE 9-30-46	Carlson	Volt	3,650	246	32	118	10	30
SE NE 13-30-47	Phillips-McKee	Tule	1,460	422	43	201	11	70
C SE SW 13-30-47	Lough 2	Tule	6,935	377	59	185	20	47
NE NE SW 34-31-47	A 1-w Listug-Olson	Benrud						70
SW NE SW 36-31-47	Wetsit 1	E. Benrud	6,935	334	40	1,654	18	56
NW NE 6-30-48	Bigtrack Little	E. Benrud	4,380	363	50	172	15	20
NW SE NE 15-30-48	Bridges 1-D	E. Tule	6,205					60
C NW NE 19-30-48	Sletvold B1	Tule	9,125	737	119	339	40	30
SW SE 20-31-48	Mule Creek 1-D	N.E. Benrud	7,665					140
SE NE 25-31-48	Hann 1 SWD	W. Long Creek	2,190					102
NW NE 29-29-49	Allotted Hall SWD	Deadman's C.	1,095	1,768	155	831	37	40
NE NW 27-29-50	Goings 1	N.W. Poplar	1,095	1,106	101	359	16	44
SE NW NE 10-28-51	Huber 1-W	Poplar	9,125					146
NW SE 10-28-51	Reynolds EPU 8-D	Poplar	2,555	5,814	709	1,894	140	50
SW NW SW 22-28-51	Bierre 1	Poplar	5,100	1,275	182	601	60	24
SW NW 7-29-51	Buck Elk 1	Poplar	1,825					
SW NW 7-29-51	Buck Elk 2	Poplar	5,570					20
SW SW 28-29-51	EPU 29-D	Poplar	1,825			1,010	62	34
SW SW SW 31-31-48	Stai 1 SWD	E. Benrud	3,650					52

* Permeability measured in millidarcys; porosity assumed to be 15%.

The data presented in Tables 6 and 7 indicate that injection in the Poplar Field has created significant pressure changes around the wells, which will reach at least 5 miles to the east and west. The pressure mound will be elongated in a north and south direction because of the interference effects of several injection wells which lie in a north-south line over a distance of about 8 miles. In the author's opinion, this pressure mound has influenced the ground-water flow pattern of the Judith River Fm. This disruption will most likely cause more flow to the south, although some increased ground-water flow to the north will occur.

There will be some westerly flow in the immediate vicinity of the injection wells, but the extent of this ground water flow reversal is not possible to estimate, although it is probably less than two miles.

A point of note is that the injection pressure, in feet of water, in the Tule Field is about 100 feet higher than that in the Poplar Field. This indicates that the overall gradient is still to the east. The large injection pressures in the Poplar Field will however, result in a flattening of the gradient between the Tule and Poplar Fields.

Any direct water quality impact due to injected water will be less than one mile to the west based on estimates for the radius of fillup. The pressure mound will have an indirect impact on water quality in that it will increase the length of the flow path. This will probably result in an increase in total dissolved solids. There will also be an indirect water quality impact caused by the displacement of the original formation water towards the west where the water quality was better (lower TDS).

5. What alternative water sources are there on the Reservation? Is data available so that an equal concentration (TDS) contour map can be constructed (i.e. greater than 10,000 mg/l, less than 10,000 mg/l for other sources of drinking water)?

Although the Judith River Fm. does supply water for livestock use on the western edge of the Fort Peck Reservation, most of the ground water used for domestic purposes is supplied from geologic units which overlie the Judith River Fm. The major sources are alluvial aquifers, terrace deposits, glacial outwash deposits and sand lenses in the glacial till. The Fox Hills, the Hell Creek and the Fort Union aquifers supply some water in areas east of Poplar, Montana. Table 8 shows the TDS content of water from a representative sample of wells tapping the major water sources. (Plenty others)

As indicated, the water quality of the alluvium and the Fox Hills is generally excellent. Note: a complete listing of wells (for which water quality data is available) is attached as Appendix 1. Some alluvial wells have TDS contents in excess of 1,000 mg/l but most have TDS contents of less than 1,000 mg/l. The TDS content of water from the Fort Union is somewhat higher, but is useable for domestic purposes.

Table 8. Total Dissolved Solids Content of Aquifers Overlying the Judith River Formation - Fort Peck Indian Reservation.

WELL LOCATION	AQUIFER	TOTAL DISSOLVED SOLIDS (mg/l)
Sec. 28 T29NR46E	Alluvium	592
Sec. 10 T29NR51E	Alluvium	809
Sec. 36 T30NR55E	Alluvium	less than 1,000
Sec. 5 T29NR51E	Alluvium	704
Sec. 32 T30N355E	Fort Union	less than 1,000
Sec. 25 T30NR45E	Fox Hills	300
Sec. 19 T28WR53E	Hell Creek	2,540
Sec. 13 T28NR58E	Fort Union	less than 500
Sec. 34 T31NR57E	Till	less than 1,000
Sec. 28 T31NR57E	Fort Union	less than 1,500
Sec. 33 T33NR44E	Alluvium	295
Sec. 29 T27NR51E	Alluvium	1503
Sec. 3 T27NR49E	Alluvium	980
Sec. 25 T28NR53E	Alluvium	2788
Sec. 2 T30NR46E	Flaxville	329

Data on the areal extent of the shallow aquifers is not available. It is apparent, however, that most of the alluvial and outwash deposits are limited in their areal extent, as are the Fort Union and Fox Hills Fms. in their subsurface extents. There are numerous alluvial aquifers throughout the Reservation, while the Fox Hills and the Fort Union Fms. are not present over the western portion of the Reservation. The Fort Union Fm. apparently extends only as far west as the Poplar Field.

Because of the absence of good maps showing the extent of the various aquifers, it is not possible to develop a map with TDS concentration contours. It is clear, however, that all of the shallow aquifers qualify as USDW's and are the major sources of drinking water in the area.

APPENDICES

1. Transcript of May 29, 1985, Public Hearing.
2. Memorandums and Correspondence relating to the Judith River Formation.
3. Summary data on the Judith River Formation compiled by Larry Monson, Fort Peck Mineral Resources.
4. Well Logs on selected wells.
5. Water Quality Data - Fort Peck Reservation.
6. Author Notes on Pressure Buildup Calculations.
7. Various Geology Reports relating to the Judith River Formation.

**AN OPERATIONAL AND ENVIRONMENTAL ASSESSMENT,
EAST POPLAR UNIT OIL FIELD,
NORTHEAST MONTANA**

Prepared for:

Assiniboine and Sioux Tribes of
Fort Peck Reservation

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- Map 2 - Long Creek East - USGS 7.5-minute quadrangle

- Map 3 - Badger Creek - USGS 7.5-minute quadrangle

- Map 4 - Poplar Northeast - USGS 7.5-minute quadrangle

APPENDIX B - Field Log - Summary of Inspected Production Equipment and Locations

APPENDIX C - Photograph Log of Inspected Production Equipment and Locations

1.0 INTRODUCTION

Holm Technical Services, Inc. (HTSI) completed an environmental and operational site inspection of the East Poplar Unit during November 1998. We completed this inspection at the request of Sonosky, Chambers, Sachse & Endreson, legal counsel to the Fort Peck Tribes in Poplar, Montana. Representatives of the Assiniboine and Sioux Tribes of the Fort Peck Reservation specified the scope of work that HTSI conducted during this November 1998 site inspection.

The scope of work includes conducting research and analysis, and preparing an evaluation and field assessment of the condition of East Poplar Unit oil field as a result of the oil and gas extraction activities conducted there. The scope of work also includes identifying any probable environmental damage due to oil field operations, and presenting the remediation options available to remedy the resulting damage.

2.0 BACKGROUND INFORMATION

2.1 Site Description and Location

The approximate center of the East Poplar Unit lies 8.5 miles northeast of Poplar in Roosevelt County, Montana. The oil field is further located in Township 28 North (T28N), Range 51 East (R51E); T29N, R50E; and T29N, R51E. The study area consists of 115 to 120 wells and associated crude oil and salt water processing facilities situated on approximately 26 sections of land within or adjacent to the designated East Poplar Unit (EPU) boundary. Appendix A contains four USGS 7.5 minute topographic maps showing the location of the wells, the processing equipment, and the EPU boundary.

The study area, located on the western flank of the Williston Basin, is approximately 65 miles west of Williston, North Dakota. Oil in the region is produced primarily from geologic strata of the Paleozoic Era. However, production within the study area consists of both oil and

natural gas. The oil is produced primarily from the Mississippian Charles formation at a depth ranging from 5,500 to 6,000 feet below surface. Natural gas is extracted from the Cretaceous Judith River formation at a depth ranging from 700 to 1,000 feet below grade.

2.2 Site Geology and Hydrogeology

The study area is situated on surface glacial till deposits of Quaternary age, Quaternary alluvial deposits of the Poplar River, or unconformable outcrops of Cretaceous Bear Paw shale (Ross et. al., 1955). The Poplar River crosses the EPU from north-northeast to south-southwest, dissecting the field into two roughly equal halves. Oil field operations are conducted with minimum distances of one quarter mile or less between field wells and the Poplar River.

Groundwater is present beneath the study area at shallow depths in Quaternary alluvial deposits of the Poplar River valley system, and in Quaternary glacial till deposits located primarily east of the Poplar River (Thamke et. al., 1996). Data from a water resources investigation report indicate that the Poplar River is seasonally a gaining stream along its course through the study area (Thamke et. al., 1997). Using the data presented in these two investigations, groundwater movement in the aquifer is generally toward the Poplar River. Subsurface flows appear relatively perpendicular to the incised river valley from substantial distances away from the present river course and turn parallel to the river as they approach the present river channel.

2.3 Site History

Murphy Oil Company discovered oil in the Charles formation of the Mississippian Madison group rocks in March 1952. Murphy initially developed the field area on 320-acre spacing, and then redeveloped the field area using a 160-acre spacing pattern. Huber Oil owned a 120-acre tract in the south central portion of the field which it ultimately developed on 20-acre spacing. Murphy drilled a pilot project in the north central sector of the field utilizing 80-acre well spacing. HTSI assumes that this pilot project resulted in marginal apparent economic gain, and thus the 80-acre development program was not continued throughout the field area.

The EPU has produced over 46 million barrels of salable crude oil as of the March 1998 production figures (Petr. Inf., 1998). Murphy also produces salt water brines associated with the crude oil in the EPU. Salinity of the brines ranges from 17,000 to over 100,000 parts per million (ppm; Thamke *et. al.*, 1997). Thamke (1997) indicates that over 232 million barrels of salt water brine was produced in association with crude oil in their study area. This salt water was disposed largely by injection into Class II salt water injection wells. Thamke (1997) estimates that 214 to 1,428 million barrels of groundwater are presently impacted by releases that occurred while handling this salt water.

The Montana Board of Oil & Gas Conservation (BOGC) promulgates oil field regulations applicable to most Montana lands. These regulations are contained in the Administrative Rules of Montana (ARM). However, the Code of Federal Regulation (CFR) lays administrative authority on tribal and allotted lands with the Bureau of Land Management (BLM). In addition, some EPA regulations apply uniformly to both fee-owned and tribal and allotted tracts.

3.0 OVERVIEW OF OIL AND GAS OPERATIONS

The following section provides background information helpful to understanding oil field development and operation. The overview is intended to highlight the major considerations encountered in the process of finding and extracting crude oil. We assume these standard methods apply to the study area, and that this background information applies to environmental and operational conditions in the study area.

3.1 Drilling Operations

Modern oil well drilling utilizes the rotary drill and its associated techniques (Gatlin, 1960). A steel rock bit is rotated to cut a cylindrical hole into the strata of the earth. The chipped and abraded rock fragments are removed from the borehole annulus via a drilling mud. Mud is normally circulated down through the hollow drill pipe to the steel bit and returns to surface via the borehole annulus.

The Williston Basin strata have several very soluble salt zones incorporated within the normally penetrated geologic section (Thamke, 1997). Muds used in this province consisted of a salt-based (salt saturated) hydraulic system during the 1950's through about 1985. After this time, oil-based mud systems became more widely utilized. A salt-based mud system is prepared using a salt-saturated brine as a basic component (Gatlin, 1960). The salt saturated mud system avoids dissolving the naturally occurring salt zones in the well and causing severe mechanical drilling problems. A clay powder is added to the brine to create a thick (thixotropic) liquid. This "mud" appears to be a liquid when pressured or pumped, but will set up or become highly viscous when pumping ceases. The clay additive helps suspend the rock particles (cuttings) and remove them from the well. Another function of the mud is to counteract any high pressure zones of water, gas, or oil encountered while drilling. Usually barium sulfate is used to weight the mud to achieve enough pressure to offset any high-pressure zones. Other additives may be utilized to combat corrosion, increase lubrication, or seal a zone with very open porosity.

The mud returns are cycled through a shale shaker which removes a large portion of the rock fragments derived during the drilling process (Gatlin, 1960). When the EPU was discovered and developed, mud returns from the shale shaker were emptied into the Reserve Pit, where the mud was stored until recycled back into the borehole. Formerly, pits were unlined, and they contained salt-based muds for the approximate six to 13 week drilling cycle. Thus, salt water from the Reserve Pit could actively percolate downward into surface aquifers, resulting in saline contamination. Modern day operations utilize a lined pit, but generally store this mud actively in steel tankage adjacent to the Reserve Pit. The modern day Reserve Pit is now used primarily for emergency situations. Reserve pit regulations are contained in ARM 36.22.1005 or in 40 CFR 112.7 for the respective fee or tribal-allotted lands.

3.2 Well Completion

The geologic strata are drilled with fresh water until the entire section containing potable aquifers is penetrated (Gatlin, 1960). A surface conductor of approximately 12- to 16-inch

diameter extending from surface to total well depth is cemented into place. The cement is placed outside the conductor pipe, and it bonds the pipe to the earth annulus. The well is generally drilled to about 10.0 to 20 percent of the anticipated final depth. An approximate nine-inch diameter surface casing is then installed from surface to the total hole depth. This surface casing is cemented in place continuously from total depth to the base of the conductor. The well is drilled to its target depth using a smaller diameter bit. Production casing is then installed from the surface to the total depth of the hole, and is cemented into place from the base of the surface casing to the total well depth.

Prior to producing the well, a wire line tool is utilized to determine that the cement bond is adequate for a continuous 50-foot zone in competent rock both above and below any zone containing producible fluids (ARM, 36.22.1001; 40 CFR 146). Holes are shot into and through the casing wall to allow the desired fluids enter the wellbore (Gatlin, 1960). Wells in the EPU either flow oil and water naturally to the surface, or are pumped through an approximate two-inch inside diameter steel tubing to the surface. A pumping unit is set at the wellhead, and a pump with a barrel-length matching the pump stroke is installed downhole adjacent to the producing zone. The second pumping unit on several of the EPU locations was installed to lengthen the pump stroke and increase the daily liquid recovery rate in that well.

3.3 Surface Production Operations

The produced gas, oil, and water may be treated in a knockout vessel (Chilingar and Beeson, 1969). This equipment is often used to separate casing head gas from the liquid portion, to reduce the easily separable water from the liquid stream, and/or to remove produced sand or sediment which would plug flow lines. The oil and water is then emptied into a heater-treater, which separates the oil from the water. Salable oil is pumped through a pipe line, stored in a tank, and is sold to a crude oil transportation company.

The produced water usually flows through a pipeline and into a tank or brine pit, where it is accumulated prior to disposal (Chilingar and Beeson, 1969). According to Mr. Tom Richmond

of the BOGC (personal communication, December 23, 1998), unlined brine pits were allowed within the EPU boundary at one time. Modern salt water injection concepts suggest that minimum cost for salt water disposal is achieved by collecting the produced water directly into a tank and injecting it as soon as is possible after production. This minimizes the cost of adding corrosion and scale inhibitors and bactericide. A bactericide is often added to limit biological growth on the formation receiving the injected brine.

Corrosion continues to be a problem associated with oil production in the study area. This corrosion may be due to electrochemical causes, anaerobic bacteria, oxygen, or aerobic bacteria (Chilingar and Beeson, 1969). Well casings are protected using impressed current to counteract the corrosion tendencies. Flow lines and equipment are protected by adding corrosion inhibitors to control acid ion, react with oxygen, and coat the steel surfaces to eliminate hydroxide buildups. Corrosion inhibitors may be high in chromous ions (chromates).

Produced water may contain calcium and other soluble cations. Mineral solubilities vary greatly between reservoir and surface conditions. Murphy uses scale inhibitors at the well head north of the Poplar River to control calcium scale. The USGS has completed previous studies of produced water (Otten *et. al.*, 1997). Otten discovered that radioactive isotopes were present in produced water in Osage County, Oklahoma. Early disposal practices and later salt water spills led to elevated radioactivity in soils near at least two oil fields in Osage County.

3.4 Enhanced Recovery

Operators may recover additional crude oil using reservoir pressure maintenance (Chilingar and Beeson, 1969). Pressure is often maintained by reinjecting produced water, or by injecting natural gas or carbon dioxide gas. Murphy found that reservoir pressure maintenance was not practical in the EPU because the natural water drive of the reservoir allows some of the wells to produce by natural flow. Carbon dioxide and/or natural gas are not presently available in enough quantity at reasonable cost to use to either inject around the field perimeter to increase oil mobility (and thus increase oil recovery), or to inject as a gas cap to displace oil back to wells on the perimeter of the field.

4.0 EAST POPLAR UNIT FIELD INSPECTION

HTSI personnel inspected the EPU during November 1998. The data were recorded in a field log book. Photographs were collected for almost every location in the study area which is either currently active or appears temporarily abandoned. The locations of the reviewed sites and equipment were recorded on USGS 7.5-minute topographic maps covering the study area. The four maps are contained in Appendix A. They are: Map 1 - Geddart Lake; Map 2 - Long Creek East; Map 3 - Badger Creek; and Map 4 - Poplar Northeast. Appendix B contains a summary of the data recorded in the field log book. This data is organized into a spread-sheet format requiring facing pages. Copies of the actual photographs are presented in Appendix C. Entries in Appendices A, B, and C are tied together via photographic reference numbers, actual EPU well numbers, and Murphy facility numbers. The maps indicate the actual locations of wells and equipment. We present these data for review.

5.0 SUMMARY OF INSPECTION RESULTS

HTSI personnel were somewhat hampered by snow cover during the site inspections. However, we feel that the inspections have identified the major environmental issues pertinent to the operating history of the study area.

5.1 Well and Facility Status

HTSI found that approximately 118 wells were drilled within the EPU. We found that 25 of the 118 wells (21.2 percent) were plugged and abandoned (P&A). The surface at these sites was generally reclaimed and usually showed minimal indication of prior use as a producing well. Based on non-daily pumper visits and disabled electrical service, we assigned a temporarily abandoned (TA) status to 47 of the 118 study area wells (39.8 percent). We also observed that 46 of the 118 study area wells (39.0 percent) were being actively used to produce oil and gas or to dispose of produced saltwater.

We identified 19 lease batteries A through S in the EPU. We reviewed all of their locations except Batteries A, G, and O, which had apparently been reclaimed prior to our site visit. We identified and reviewed four active unit batteries, the North Central Battery (formerly Battery R), the South Central Battery (formerly Battery S), the Huber and McGowan Batteries. We identified and reviewed six salt water disposal stations (old 5D, new 5D, 1D, 6D, 80D, and 8D). We also reviewed three equipment yards and one custody transfer point. HTSI personnel visited 30 of the 33 locations, finding 33.3 percent (11/33) of the sites still active, 42.4 (14/33) percent were TA'd, and 24.3 percent (8/33) were dismantled and reclaimed to various degrees.

5.2 Transformers

HTSI visited approximately 148 locations/facilities during our site inspection. We found that 61 of these sites (41.2 percent) had transformers. Most of these transformers are still used for the power requirements of producing petroleum from the study area. However, there are transformers present on 12 TA'd locations.

5.3 Containment Dikes

HTSI personnel witnessed a spill at EPU-31 during our site inspections. This spill consisted of salt water and crude oil. Should the leak be discovered before significant quantities of produced liquids are spilled, and the spill contained to the bermed area, such spill is both limited in areal extent and easily cleaned up. Wells like EPU-101, which is southeast of the South Central Battery, have no berms at all. Many other wells had gaps in their berms. The purpose of the berms is to contain any well head spill to the location itself. Maintaining the berms requires continual effort by the operator. Enforcement requires vigilance by the regulating authorities.

5.4 Production Chemicals

Many of the inspected locations are equipped with approximate 150-gallon poly tanks. The primary chemical usage at the site appears to be corrosion inhibitor. These chemicals are

generally in either poly tanks on stands, or in 55-gallon drums on drum racks. Good site management uses these practices. HTSI personnel did not identify any apparent places where chemical spills have occurred within the study area. However, we did find a two-gallon plastic jug labeled Roundup (left of the base of the fulcrum beams) at well EPU-39 (Photo 2-16, Appendix C). This suggests that Murphy controls weeds at their wells and facilities using herbicides.

5.5 Crude Oil Spills

Crude oil spills were evident at almost every location which had not been reclaimed. Clay soils have a significant capacity to adsorb spilled crude. However, gravelly and/or sandy locations have poor crude oil adsorption capacities. Large volume spills on gravelly locations, coupled with shallow, near surface aquifers, may result in crude oil product floating on groundwater. Spill regulations are contained in 43 CFR 3162.5-1 and ARM 36.22.1103. We also noted that apparent success of surface reclamation efforts is usually evidenced by the lush grass growing right up to the wellhead at many reclaimed sites.

5.6 Stressed Vegetation

HTSI observed apparent stressed vegetation at 42 of the 148 inspected sites (28.4 percent). We observed three generations of flow lines near Battery P. The detrimental effects of corrosion on steel pipes and vessels in the study area have apparently resulted in significant salt water spills. Historically, one salt water injection well, a Mesa Petroleum well near the South Central Salt Water Disposal facility, developed a casing leak where the cement bond failed around the injection zone. Reportedly, this well flowed salt water freely to surface for three months while a relief well was drilled to control the "run-away" well. Thamke's results indicate abnormally high near surface electrical conductivity in the study area near this well and in many other areas due to elevated groundwater salinity. HTSI viewed stressed vegetation adjacent to many facilities which appear to correlate with both Thamke and recent study area salt water production and disposal facilities. We did not collect radioactivity measurements (Otten, 1997). In our opinion, the salt water problem constitutes the most difficult and pervasive problem we can identify through our inspections.

5.7 Waste Drums

HTSI personnel observed waste drums at five of the 148 sites we inspected. These drums, at EPU-101, EPU-114, EPU-110, North Central Battery, and E-Battery, were normally numbered and placed on palates. We also inspected EPU-46, which had palates with 9 numbered drums. The drums at EPU-101 and EPU-114 were not on palates. All drums except one at EPU-110 were tightly covered. The open drum at EPU-110 appeared to contain either waste oil or crude oil and expended oil filters. The open drum will collect precipitation, which will eventually displace the oil contained within the drum.

5.8 Junk

Many of the locations and facilities had junk scattered around the Murphy occupied surface area. Most TA'd wells had pumping units which have become the source of parts for other similar pumping units within the field boundary. The presence of the abandoned junk, steel vessels, and equipment may be construed or classified as solid waste. Rules for solid waste management are contained in 40 CFR Part 260 and ARM 17.50.500 et seq. We did not inspect the abandoned piping or equipment for scale deposits or perform a radioactivity survey. However, we do note that Otten *et. al.* (1997) found radioactivity associated with scale deposits in abandoned piping and oil field treatment and storage vessels.

5.9 Pits

We inspected eight pits within the EPU and one at EPU-46, which is outside the boundary. The pits at South Central Salt Water Disposal Station, EPU-80D, Salt Water Disposal Station 1D, and Salt Water Disposal Station 5D either have probable saltwater with total dissolved solids exceeding 15,000 ppm or crude oil. All these pits are lined and fenced. However, the pits at the South Central Salt Water Disposal and Salt Water Disposal Station 1D have no or partial netting. The regulations for operating pits are contained in ARM 36.22.1223 or regulatory orders from 43 CFR 3160 et seq. The pits at EPU-60 and EPU-23 have sludge in

the pit, but are either not lined, fenced, or netted. The pits at EPU-46 and east of EPU-19 are dry pits. There is also a poorly fenced pit containing water at the McGowan Battery which is neither lined or netted. Proper pit closure methods are generally determined using chemical analyses of pit contents.

6.0 DISCUSSION OF SOLUTIONS AND REMEDIATION METHODS

The operational shortcomings witnessed within the EPU require solutions. The environmental problems either witnessed or suspected may require potential remediation methods. The following is a discussion of the potential remediation methods for the items presented in the previous section.

6.1 Temporarily Abandoned Wells and Facilities

Rules pertaining to TA are contained in ARM 36.22.1303 or 43 CFR 3162.3-4. We labeled many wells and facilities as TA'd. These facilities appear of no further value to mineral extraction. The arguments for properly plugging and abandoning wells within one year include the minimization of salt water and/or crude oil movements from formation to formation, or ultimately escaping to the surface or into potable groundwater. HTSI personnel noted an apparent salt water leak at well EPU-69, in the north central portion of the field. This leak was occurring from the wellhead at this location with mostly sand and gravel surface material. Well EPU-69 is a TA'd well. The arguments for allowing longer TA periods include possible future mineral recovery using enhanced recovery methods. Some enhanced methods may not be economic today, but may be practical or available in the near future.

HTSI personnel observed that many of the old lettered batteries were obviously being dismantled, removed, and reclaimed during our inspections. The recent construction activities tend to obscure the effectiveness of inspections. A follow-up review of these facilities at some later date will confirm if Murphy has completed reclaiming these areas. In part, reclamation consists of hauling off equipment and debris, discing, and seeding with native grass.

6.2 Transformers

Most of the wells drilled within the unit boundary were completed during the 1950's and 1960's. Montana Dakota Utilities provided electrical hookups to power the operations in the EPU. Transformers installed during this period undoubtedly contain oils with poly-chlorinated biphenyls (PCBs) in concentrations exceeding 50 parts per million (ppm). Transformers removed when the site or location is dismantled and reclaimed are not of concern to the landowner. However, it is imperative that transformers are removed prior to lease termination.

The options for proper disposal include getting a qualified company to recycle the transformer and its contents. Transformer and contents could be shipped to a transfer, storage, and disposal (TSD) facility for storage, but the owner of record then continues to be liable for the PCB material from cradle to grave (until the PCB's are destroyed). A third option has qualified personnel remove the transformers from their poles, collect samples for chemical analysis (to characterize the contents), and ship this material to the most appropriate site to recycle or to burn the material for energy recovery at a licensed facility. The regulations pertaining to PCB disposal are contained in 40 CFR 761.20 and ARM 17.54.312.

6.3 Containment Dikes

In Montana, the rules and regulations pertaining to oil field operations originate from the Montana BOGC (ARM 36.22.101 et seq.) or the BLM (43 CFR 3160 et seq.). Containment dikes or berms were incorporated into the regulations in the 1980's. These regulations are generally enforceable by the Montana BOGC everywhere within Montana except on Tribal or Allotted tracts on designated Indian reservations. Enforcement authority on Tribal or Allotted tracts belongs to the BLM.

6.4 Chemicals

HTSI personnel did not find any apparent spills of production chemicals prior to their use within the study area. Chemical usage appears in accordance with sound management practices. Therefore, we do not comment on either operations or remediation options for oil field chemicals.

6.5 Crude Oil Spills

Spills of crude oil and produced water exceeding 50 barrels (42 gallons per barrel) require notification of either the BOGC or BLM. The operator must promptly control the spill and clean up the resulting spilled material. Impacted soil may be treated (ventilated) in place to reduce the benzene component of the crude oil which could render this material a toxic waste (40 CFR 261; ARM 17.54.331). The crude oil and salt water produced is generally exempt from the provisions of the Resource Conservation and Recovery Act (RCRA) where the oil extracted from the ground is placed into a transportation system with the intent to insert the crude into the petroleum refining process [40 CFR 261.4(a)12]. There is an argument for this exemption terminating for crude oil and saltwater where the crude oil cannot be inserted into a conveyance leading into the petroleum refining process.

A ten barrel release of crude oil and saltwater that collects into a water course obviously flowing into a surface water body or stream, or any release which imparts a sheen on the groundwater constitutes a release reportable to either the EPA or Montana Water Quality Division. BOGC rules governing safety, including spill reporting, are contained in ARM 36.22.1101-1105. The BLM follows rules in 43 CFR 3162.5-1.

Small amounts of crude oil stained soil could be treated in place by cultivating this soil several times per month from April through October. The discing and reseeding operations used to reclaim the plugged and abandoned well sites appears to be very successful. Larger crude oil spills may require berming to contain the spill and use of vacuum trucks to pick up the spilled crude oil. The recovered oil can then be routed through normal crude oil processing facilities,

used for dust suppression, or hauled to the nearest saltwater disposal well for disposal by injection. For losses of crude oil on the very gravelly locations adjacent to the Poplar River, it is possible to have crude oil reach the groundwater. If a measurable thickness of free oil is detected on the groundwater, this free oil would need to be recovered. The Montana Water Quality Division tends to follow the regulations pertaining to free product recovery as outlined under the Underground Storage Tank Program. Free product recovery requires that the operator define the extent and severity of the plume, install a recovery well(s), trench, or pit, and recover the product until the thickness of such product is less than 0.01 foot. Although HTSI personnel can not generally determine the presence of free product on the groundwater via a site inspection, we did observe oil on water in an underground valve housing at the North Central Battery. Via our inspection, we did not determine if the water represents the actual groundwater surface in the North Central Battery vicinity.

During August 1998, strong winds blew a heater treater over in the N Battery. Crude oil and salt water may have spilled at this facility. Such occurrence would allow produced liquids to spill until the pumper crew next checks the facility. If this occurs on a Friday evening, it potentially may continue until discovered on Monday morning. Berms may have limited the area impacted by this spill.

6.6 Stressed Vegetation

HTSI personnel noticed that at least three generations of crude and salt water flow lines were installed between EPU-37 and the P-Battery, located in the northern portion of the study area. The corrosive nature of the produced liquids is obviously the cause for many of the salt water spills at the site. The conversion of the flow lines at the site to the concrete asbestos pipe is an attempt by Murphy to both lower their ultimate operating costs and to minimize the number and severity of the salt water spills at the site.

This salt water raises soil salinity and ultimately decreases the productivity of the soil. A no action policy allows the natural precipitation to slowly leach the elevated salt content from the

soil. The no action method allows the salt to collect into either the runoff or the groundwater systems. Soil washing could be utilized to quickly strip excess salinity from the soil. However, this process uses large volumes of potable water to create large volumes of saline water requiring disposal. Murphy uses a process that amends the impacted soil with manure and straw. The increased organic content of the soil increases the salt bearing capacity of the soil. Although this does not reduce the elevated salinity, it does restore the soil's productive capacity to some extent while reducing the rate at which the salt is released into the surface and/or groundwater system.

A no action policy concerning the Poplar River and its saline contaminated aquifer allows the continuation of the existing conditions without applying any remediation efforts to alter the saline conditions. As a receptor-based remedy, extending Poplar's community water intake to a point near the study area's north boundary would improve Poplar's water supply (if impacted). However, the remedy to the surface owners' loss of shallow aquifer usage would require these owners to have access to the Poplar community water supply.

Reducing the salinity of the shallow aquifer within the study area requires the careful site characterization that is presented in the USGS Water Resources Investigations report (Thamke *et al.*, 1997). A well or field of wells is installed to withdraw high salinity water from the aquifer's saline plume. Disposal of the saline groundwater would require its injection in a permitted Class II injection well.

The high salinity of produced salt water suggests a high cation load in this water. We do not presently know the chemical composition of the produced water. We do know that scale inhibitors are used in a portion of the study area. Since Otten's studies (1997) suggest that radioactive isotopes may be present, the salt water spill impacted soil may have to be excavated and shipped to an acceptable disposal site. However, proper disposal is generally determined after obtaining data from chemical and radioactivity analysis of soil samples from the spill areas.

The HTSI study of the salt water problem is specifically meant to augment previous work done in the area (Thamke, 1997). Tribal representatives requested comments on the potential solutions for solving the operational problems and for site remediation.

6.7 Drum Waste Disposal

The contents of the drums within the study area must be known for disposal. One method for disposal brings in a licensed hazardous waste transporter, who opens the drums, pumps the contents into his tanks, and hauls the contents to a Class II injection well for disposal. This assumes that the contents are still within the definition for the oil and gas RCRA exemption (see Section 6.5). Otherwise, the drum owner must call in a licensed shipper, manifest the waste, and ship it to a TSD for storage, recovery, or incineration. Without adequate knowledge of what is actually in each drum, the contents would require sampling and laboratory analysis. Obviously, Murphy has more than 1,000 kilograms of waste in these drums, and this quantity of waste should be shipped within 90 days. Rules pertaining to shipping and manifesting hazardous wastes are contained in 40 CFR 264 and ARM 17.54.100 et seq.

6.8 Junk Disposal

Much of the steel within the study area could be salvaged and recycled. An active effort to inventory the pumping units and parts scattered through the study area could result in rebuilding several entire pumping units. The steel frameworks, available in excess, could be recycled. Barring radioactive scale, abandoned treaters and knockout equipment can be rebuilt and sold, or sold for scrap. Wood and other debris could be collected and hauled to an industrial landfill.

6.9 Pit Closure

Dry pits can be bull-dozed, leveled, and the surface reclaimed. Exxon Corporation closed salt water and oil containing pits in Belle Creek Field by solidification using fly ash. A slurry mixer worked in one corner of the pit mixing pit liquids actively with fly ash. Before the fly ash can fully hydrate, the mixture is pumped and placed into the farthest corners and edges of the open pit. Thus, fly ash mixture displaces the entire contents of the pit back to the slurry mixer until the pit has been closed. A synthetic liner is installed to cover the closed pit. The liner is covered by 12 to 18 inches of soil, which is then planted in native grasses. For Murphy to use this

method, they would need information pertaining to the full cation analysis of pit contents.

Radioactive isotopes, if present, could render this closure method as inappropriate (Otten, 1997).

7.0 SUMMARY AND CONCLUSIONS

Based on our observations during our review of the study area, we offer the following:

1. The EPU has been operated as an oil field for more than 45 years. Its operating condition appears similar to other oil fields of similar size.
2. Approximately one fifth of the EPU wells are currently P&A'd. Another two fifths of the EPU wells are TA'd. Wells no longer serving the purposes of extracting oil and gas are TA'd and should be P&A'd within one year of when that well ceased being useful. Unless Murphy has plans for a secondary recovery effort in the EPU using the TA'd wells, those 47 wells should be P&A'd.
3. Transformers are being removed from the P&A'd sites with relative regularity. However, the Fort Peck Tribes should be aware that it is imperative that the transformers be removed by Murphy or MDU prior to lease termination.
4. Many locations have no or partial berms. Berms limit the lateral extent of spills where they occur within the locations or other facilities within the study area. Berms should be installed and maintained on all active locations.
5. Murphy is converting to concrete asbestos flow lines within the study area. Although this is an expensive remedy, the diminished future repair costs and the lesser number of flow line failure caused spills and their cleanup should provide an economic incentive to install the new flow lines. The judicious use of production chemicals and more frequent equipment inspections can also reduce the number and severity of failures in pumps, pipes, vessels, and injection wells.

6. General crude oil and salt water spills of 50 barrels require notification of the Montana BOGC or the BLM. A ten barrel spill where impinging on a dry watercourse, or a sheen imparted to surface water require notification of the Montana Water Quality Division or the EPA. Any spill requires prompt corrective action.
7. Murphy apparently is successful in reclaiming crude oil spills around P&A wells. This is especially true at the sand and gravel locations. However, sand and gravel locations have limited capacity to absorb crude oil from spills. This limitation could allow the spilled crude oil to accumulate on the groundwater for producing wells near the Poplar River. Any accumulation of crude oil on the groundwater requires recovery of the crude until its thickness on the groundwater is less than 0.01 foot.
8. Salt water contamination constitutes the most pervasive and difficult problem encountered during our site inspections, apparently existing in 28 percent of the reviewed sites. We assume that the addition of manure and straw will improve soil productivity in the near term. However, the salt from these spills apparently continues to leech and invade both the surface and groundwater systems in the study area. We did not look for radioactivity in either the soil or equipment we observed.
9. Murphy has six locations in the study area where split-ring waste drums are accumulated. The amount present could classify Murphy as a large quantity waste generator. Murphy should properly dispose of this material in accordance with the existing regulations.
10. Murphy should dispose the steel, wood, and plastic material present at many of the locations throughout the study area.
11. We observed four salt water injection unit emergency pits in the study area. Two of these pits have no net. The McGowan Battery pit is not fenced, not lined, and has no net. Of four other pits, two have sludge. Proper pit closure requires chemical and radioactivity analysis of soil and water samples. Murphy should close the unused pits.

8.0 RECOMMENDATIONS

Based on the preceding summary and conclusions, we recommend the following:

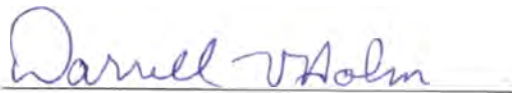
1. The Fort Peck Affiliated Tribes should press Murphy to P&A any wells one year after their TA status begins. The BLM and the Montana BOGC have jurisdiction over TA and P&A wells in the study area. As an alternative, you could request that Murphy disclose any plans for a secondary oil recovery effort within the EPU.
2. Tribal inspectors should diligently review the temporarily abandoned sites as they as are permanently abandoned to ensure that Murphy or Montana Dakota Utilities removes transformers and other electrical equipment from these locations prior to lease termination.
3. Murphy should install and maintain berms on all active locations. The Montana BOGC and BLM should be encouraged to inspect the entire study area on a periodic basis to ensure compliance with the existing regulations. Tribal inspectors should review the operating locations and batteries within the study area to ensure that berms are in place to limit surface damages from any future crude oil and salt water spills.
4. We recommend that locations adjacent to the Poplar River, when P&A'd, are assessed for the presence of crude oil on the groundwater by a competent environmental professional.
5. Due to the frequent construction encountered within the study area involving equipment removal and reclamation, we recommend that the salt water stressed areas be reviewed during the spring of 1999. This review should also include soil and water sample collection and analysis to provide documentation of the severity of the salt impacted soil within the study area. The work should also include measuring radioactivity of scale in abandoned pipe and vessels and salt water spill areas.

6. The Fort Peck Affiliated Tribes should require that Murphy remove and properly dispose any split-ring drums on Tribal, Allotted, or Indian-owned lands as soon as possible.
7. Murphy should be required to close any unused pits in accordance with appropriate chemical and radioactivity data, and to fence, line, and net those pits currently in use.
8. Tribal inspectors should require Murphy to remove and reclaim or dispose the abandoned equipment on Tribal or Allotted tracts within the study area. The inspections should include requiring and ensuring disposal of wood, metal, and plastic debris on these tracts.

9.0 LIMITATIONS

HTSI completed this work in accordance with the generally accepted practices followed by other consulting firms conducting similar studies. HTSI observed that degree of care and skill generally exercised by other consultants working under similar conditions. HTSI's findings and conclusions must not be considered as scientific certainties, but as opinions based on our professional judgement and the data gathered during the course of this investigation. Other than this, no warranty is implied or intended.

Prepared and submitted by:



Darrell V. Holm, HTSI Project Engineer

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APPENDIX A

USGS 7.5-minute Topographic Maps

APPENDIX B

Field Log - Summary of Inspected Production Equipment and Locations

**EAST POPLAR UNIT
PHOTO LOG
KEY TO ABBREVIATIONS**

LEGEND:

WELL NO.

EPU	East Poplar Unit
G-Bat	Battery G
S. Cent.	South Central Battery
SWD-8D	Salt Water Disposal 8D
SW6	Salt Water Station 6
N. Cent.	North Central Battery
xfer. stn.	Transfer station
SWD	Salt water disposal
WB-1	Wagner-Brough Well 1

WELL STATUS

P & A	Plugged & Abandoned
TA-bullplug	Temporarily abandoned
Abd	Abandoned
trans. stn.	Transfer station
SW	Salt water
disp.	Disposal
SWD	Salt water disposal
Veg.	Vegetation

TRANSFORMERS: SERVICE POLES

Not Rec.	Not recorded
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CHEMICALS

150gal.poly	150-gallon polyethylene
Corr. inhib.	Corrosion inhibitor
3 55gal met	3 55-gallon metal
2 55gal dr.	2 55-gallon drums

CRUDE SPILLS

Sludge betw.-	Sludge between
Lots w/in berm-	Lots within berm
Paved w/ oil-	Paved with oil
Some ol' stain-	Some oil stain
NW quad-loc.-	Northwest quadrant
	of location
(but v. muddy)-	(but very muddy)
S-PU & well-	South of pumping unit
	& well
5'rad.-sludge	- 5 foot radius-sludge

WASTE DRUMS

1 w/ yel 5	1 with yellow #5
Blue 55gal	Blue 55-gallon

STRESSED VEGE.

Location w/o plant life	
Location without plant life	
E,SE off loc.-	To E,SE off location
Sparse on loc.-	Sparse on location

JUNK

Pipe,5gal	Pipe, 5-gallon can
Bldg junky	Building junky
Trash bbl	Trash barrel
Abd vessel	Abandoned vessel
Conc. asb.	Concrete asbestos pipe
Counterwts	Counterweights
PU & parts	Pumping unit & parts
PU on loc.	Pumping unit on location
Kitchen chr.	Kitchen chair
Serv. pole	Service pole
Pipe & fits	Pipe & fittings
100gal ves.	100-gallon vessel
Elec. serv.	Electric service
Rusted culv	-Rusted culvert

COMMENTS

eval.	evaluation
vege.	vegetation
loc.	location
re-eval.	re-evaluate
spr.	spring
KO	Knockout
SW	Salt water
environ.	environmental
rev.	review
TA	Temporarily abandoned
stn.	station
prog.	progress
chem. inj.	chemical injection
mkr.	marker
PU	Pumping unit
MDU	Montana Dakota Utilities
SW in GW	Salt water in groundwater
bkgd	background
P & A	Plugged & abandoned
fld.	field
add'n	addition
conc. asb.	concrete asbestos

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size	Type
EPU-20	Pumping	1-1	SE-NW	3	In use	No E berm	150gal poly	Corr. inhib.
EPU-104	Flowing	1-2	SE-NW	3-Not in use	Disabled	None	None	
EPU-17	P&A							
EPU-116	Pumping	1-3	S-N	3	In use	None	None	
G-Bat	Battery	1-4	SSW-NNE			None		
EPU-76	P&A							
EPU-99	P&A							
EPU-44	P&A							
EPU-55	Flowing	1-5	SE-NW	3-Not in use	Disabled	Bermed	None	
EPU-74	Uncertain							
EPU-26	P&A							
EPU-3G	P&A							
EPU-22	TA-bullplug	1-6	SE-NW	Not Rec.	Not Rec.	None	None	
H-Bat	Abd Tanks	1-7	SE-NW			None	None	
	Abd Well	1-8	S-N			None	None	
	Abd treater	1-9	NE-SW	Removed	Disabled	No E berm	None	
EPU-32	TA-bullplug	1-10	SSW-NNE	Removed	Disabled	No S berm	None	
EPU-101	Flowing	1-11	NE-SW	3	Disabled	None	None	
EPU-9	Pumping	1-12	ENE-WSW	3	In use	No E berm	None	
K-Bat	Abd treater	1-13	N-S	Removed	Disabled	Bermed	None	
	New flowline	1-14	WNW-ESE					
EPU-100	Pumping	1-15	NE-SW	3	In use	No N berm	None	
						GapNE,NW		
EPU-68	TA-bullplug	1-16	E-W	3	On ground	None	None	
EPU-24	TA-bullplug	1-17	NW-SE	Removed	Removed	Not eval.	None	
EPU-15	Pumping	1-18	E-W	3	In use	No E berm	150 gal poly	Corr. inhib.
EPU-7	Pumping	1-19	SE-NW	3 4th pole W	In use	No NE berr	150 gal poly	Corr. inhib.
						Weak @ NW		

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
4	Well head	Not observed			Lots of snow limited evaluation
4	Flow line	Not observed			Spill north of well head
4					Site reclaimed
4	Well head	Not observed			Propane pup at well head
4		Not observed		Pipe	Replacement well for 17
4					Site reclaimed
4					Site reclaimed
4					Site reclaimed
4	In & on berm				Recompleted as gas well
4					On fee land - no road- did not review
4					Site reclaimed
4					Did not locate marker
4	Not observed	Not observed			Lush grass up to well
4	Sludge betw.	None at tanks		Cable	Tanks rusted out - sell for scrap
4	Not observed	Not observed			Concrete pad in place - no lease ID
4	Not observed	Not observed			Fire tube plate gone - sell for scrap
4	Snow limited	E of well head			Scavenged pumping unit
4	S,SE,W of well	No veg to W	1 w/ yel 5	Pipe,5-gal	Crude flowed W of location, no berm
4	Well head	Not observed			Access E of well; no or weak E berm
4	Treater,W-line	Not observed		Bldg junky	Unit abandoned for central crude processing
4					
4	Well head	Wellhead		Gear oil jug Trash bbl	Snow limited evaluation, but vegetation is sparce.
4	Not observed	Not observed			Concrete pad and railing intact
4	Snow limited	Not observed			Farmer reclaimed up to wellhead.
4	Well head	Wellhead			Snow limited eval., vege. is sparce.
4	Lots w/in berm	Not observed			Scavenged pumping unit on loc'n.

WELL NO.	WELL STATUS	PHOTO NO.	DIREC-TION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size Type	
EPU110	P & A							
EPU-6	Flowing	1-20	N-S	3	Disabled	No N berm	None	
S Cent. (R-Bat.)	battery	1-21	NE-SW	3	In use	Bermed	None	
	trans. stn.	1-22	N-S				None	
	tanks	1-23	WNW-ESE				None	
	SW pit	1-24	ENE-WSW			Bermed	None	
EPU-12	Pumping	1-25	SE-NW	3	In use	No E berm	150 gal poly	Corr. inhib.
SWD-8D		1-26	SE-NW	3	In use	No N berm	500 gal poly	Corr. inhib.
		1-27	E-W				55 gal steel	Scale inhib. Various
Pumper's shed storage		2-1	SE-NW				6 barrels	Various On rack
EPU-8D	SW disp.					No berm		
Huber 5	TA-bullplug	2-2	ENE-WSW					
Huber	oil spill	2-3	NE-SW					
battery	treaters	2-4	SW-NE	3	Disabled	No W berm		
	salt stress	2-5	SW-NE					
	trans.stn.	2-6	SSW-NNE					
	tanks							
Huber 4	TA-valve	2-7	N-S					
Huber4A	Pumping	2-8	NW-SE	3	In use	GapWberm	55gal steel	Corr. inhib.
Huber 2	TA	2-9	N-S	Removed	Disabled	None	None	
Huber 6	SWD	2-10	W-E	Removed	Removed	None	None	
EPU-67	P & A							
EPU-11	P & A							
Huber 3	TA-bullplug	2-11	N-S	Removed	Removed	Partial	None	
Huber 1	Pump on timer - TA?	2-12	SE-NW	3	In use?	No E berm	55gal drum on cradle	Corr. inhib.
EPU-14	TA-bullplug	2-13	N-S	Removed	Removed	None	None	
F-bat	backhoe pit	2-14	SE-NW			None	None	
	treater, tank trans. pump	2-15	S-N	Removed	Removed	None	None	

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
4					Recently reclaimed; re-eval. spr. 99
4	Messy well	Not observed			Recent new flow line W to battery
4	Paved w/ oil Sludge@tanks			Flow line	Water KO and treater-new install Not much mess yet Sludge and oil around valves Water in pit; lined, fenced, no net
4	Inside berm	N,NE of berm		60' Casing	Possible SW stressing outside berm
4	Not observed	S of berms		Skid vessel	Site is junky - lots of chemicals in
4	Not observed			Frac tank	barrels on racks. EPU-8 is just
				Flow line	north of buildings. Need spr.99 rev.
4	Not observed	Not observed		N of bldg.	Junky, but all in one small area
4	Not observed	S of area			Probable extreme environ. impact
4	In&SW of berm Lots o' sludge Snow limits	S,SW of berm E,SE of berm		Pipe&fitting Wire&cable	Probable TA well - crude spill thru S berm, SW cor.-S treater rusted out - sell for scrap. Stressed soil outside bermed area. Transfer strn and 2 tanks in use? W tanks open, rusted out-sell for scrap. Spr99rev
4					Pad, partial railing; needs reclaiming
4	E of wellhead				Lots of oil; may go over E berm
4	W of wellhead				Lots of old oil on this location
4	S of wellhead	All of location		Abd vessel 5gal bucket	Probable high risk area Needs spring 99 review
3					In cultivated field - no marker
4					Reclamation in prog.; review spr. 99
4	Snow limits	Sparse			Farmer is reclaiming location, berms
4	E&W wellhead Onto road to E wellhead	Sparce @ wellhead			Messiest location thus far
4	Not observed	Lush grass		1.25" cable	Lush grass near well head
4	Probable To NW in valve Snow limits	Probable Unsure		Conc.-asb. pipe	Pipe being replaced,site reclaimed. Sludge around tank-too much snow activity to fully evaluate; spr 99 rev

WELL NO.	WELL STATUS	PHOTO NO.	DIREC-TION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size Type
EPU-39	Pumping	2-16	SE-NW	3	In use	No S berm	150gal poly Corr. inhib. 2gal plastic Roundup
EPU80D	Pit	2-17	N-S			Full berm	None
	Wood tank	2-18	ESE-WNW			W&SW berm	
	Stress Veg.	2-19	ESE-WNW			No NW berm	
	SWD	2-20	SW-NE	3	In use	E&N berm	300gal poly Corr. Inhib.
EPU-41	TA-bullplug	2-21	WSW-ENE	Removed	Disabled	None	None
EPU-45	TA-bullplug	2-22	SW-NE	Removed	Removed	None	None
EPU-5	Pumping	2-23	SE-NW	3	In use	Weak to E	150gal poly Corr. inhib.
C-Bat	treater pump tanks	2-24	SE-NW	3	Disabled	Bermed	None
		2-25	SSE-NNW				
Repairs		2-26	ESE-WNW				
EPU-85	TA?	2-27	E-W	3	In use?	Weak to E	None
EPU-18	Pumping	3-1	SE-NW	3	In use	None E, N	None
EPU-1	Flowing	3-2	SW-NE	3	Panel open In use?	Bermed	None
EPU-16	TA?	3-3	NE-SW	1	Disabled	No N berm	None
EPU-4	TA-valved	3-4	SE-NW	3	In use?	Bermed	None
EPU-3	TA-bullplug	3-5	N-S	Removed	Removed	None	None
EPU-88	Pumping	3-6	ENE-WSW	3	In use	No S berm	None
EPU-43	TA-bullplug	3-7	E-W	Removed	Removed	None	None
EPU-66	Pumping	3-8	SE-NW	3	In use	No SE, NW berms	150gal poly Corr. Inhib. 150gal metal dispenser

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
4	Widespread	Sparse		Pump unit parts	Oil on standing water - NW berm. Extra pumping unit-very scavenged.
3	Not observed	E & SW In&out of berm Not observed		1.25" cable cardboard	Pit lined and netted. Wood tank in use. Stressed soil N of berm, but especially to SW near coulee. High risk area for saltwater. Rev. spr. 99.
3	Snow limits	Sparce veg.		Pumping unit parts	Gravel may not support vegetation.
3	E of wellhead Snow limits	Not observed		Cable	Well is west of old Model A
4	Wellhead & N Snow limits	Not observed		Culvert	Snow limited evaluation of bermed Counterwts. area S of well.
4	Treater & W Around pump Sludge @ tanx	Not apparent		Pipe&valve Pipe - dike	This site should be reclaimed in spr. 99; should be re-evaluated then.
4					From C-bat, view of line break repair. Should review in spring 99.
4	S, N, SW-well	Sparse			Power shut off, no chems, status ?
4	Snow limits Wellhead	Not observed		PU & parts Gear oil jugs	Too much snow to fully evaluate
4	SW wellhead Snow limits	NW berm area		Pump unit Pipe&fitting	Lot of crude, too much snow to eval. Should review spring 99
4	W of wellhead Sludge NW,SE	Not observed		Tubing PU on loc. Frac tank Pipe&fitting	Tubing laid down, no rods. Beam pump disassembled, on ground. Flow line laid W recently. I should review status in spring 99.
4	W of wellhead On N berm	Not observed		Pump unit	Status is a ?, should review spr. 99.
4	E&Wwellhead	Not observed		Cable	Site may be in reclamation.
4	Wellhead	Not observed		Gear oil jug:	Some facility removed 50' E of well. Review reclamation efforts spr. 99.
4	Not observed	Not observed			Pad & well in new broken sod field.
4	E&Wwellhead	Not observed			Mud obscuring soil stain - becomes similar in color to crude spills.

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size Type	
Q-bat	treater	3-9	NW-SE	Removed	Disabled	Bermed	None	
EPU-89	TA-bullplug	3-10	W-E	Removed	Removed	None	None	
EPU-64	P & A							
EPU-83	Pumping	3-11	SE-NW	3	In use	No S berm	2-55gal	Corr. inhib.
EPU-51	P & A							
EPU-57	TA-bent rod	3-12	SW-NE	3	Panel open	No N berm	None	
EPU-114	Awaits pipe	3-13	NW-SE	3	In use	None	None	
EPU-42	Flowing	3-14	SW-NE	3	In use	N,W berm	55gal drum	Scale inhib.
N-Bat	Tanks	3-15	ESE-WNW	3	Disabled	N, W, S	None	
	Trans pump Treater	3-16	SE-NW			None	None	
B-Bat	treater	3-17	NE-SW	Removed	Removed	None	None	
SW-6	tanks	3-18	E-W			W,N berm	None	
	salt spill	3-19	SE-NW					
EPU-86	P & A							
EPU-29	P & A							
EPU-81	TA-bullplug	3-20	W-E	Removed	Removed	None	None	
EPU-62	TA-shut in	3-21	E-W	3,3rd pole N	Disabled	SW,W,NW	None	
EPU-28	P & A							
EPU-103	TA-bullplug	3-22	E-W	Removed	Removed	None	None	
EPU-47	TA-valve	3-23	E-W	Removed	Disabled	None	None	
EPU-79	TA-bullplug	3-24	NE-SW	Removed	Removed	None	None	
EPU-25	P & A							
EPU-97	Pumping	3-25	SE-NW	3	In use	No E berm	None	
EPU-96	TA rods	3-26	WSW-ENE	3	Disabled	Gap to E	None	
EPU-110	Pumping	3-27	NE-SW	3	In use	None	None	

MAP NO	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
4	N of treater	Not observed		5gal bucket	Facilities abandoned - should be re-claimed. Should review in spr. 99.
4	Not observed	Not observed			Pad & well in new broken sod field.
4		Lush grass			Site reclaimed
4	Paved w/ oil	Not observed			Workover rig on location.
4					Site reclaimed.
4	E,W,N - well	Not observed		Pump unit	
4	Wellhead	Not observed	Blue 55gal	Pipe&valve	Awaits flow line to begin production.
4	Wellhead	Not observed			Flowing well with electric chem. inj.
4	Around tanks	Construction			Treater blew over; 114 is down & 42 is repiped. Area being dismantled; should review this spring 99.
4	Around pump	Construction			
4	Around treater	Construction			
4	Around treater	Location		5gal cans-6	Treater shack very oily, trashy. Two tanks full of sludge. Strong evidence of salt stress to W, NW- rev. spr. 99;
4		Location	Tank sludge		
4					Site reclaimed, no mkr.- plowed field
4					Site reclaimed.
4	Not observed	Not observed			Lush grass up to wellhead.
1	W wellhead	Not observed			Oil on SW berm; loss direct to river.
4					Surface cultivated & reseeded.
4	Not observed	20' radius-well			Pad remains; needs reclamation.
4	Some ol' stain	Not observed			Pad, railings, & tie downs remain.
4	Some ol' stain	15' radius-well			Pad, railings, & tie downs remain.
4					Site reclaimed.
4	Loc. & N berm	Not observed			Location is fairly gravelly.
4	Wellhead	No plants		Belt&guard Pump unit	Scavenged PU; gravelly location; saltwater leak from wellhead.
4	Location	Location	3-yellow #7		Gravelly, very messy location.

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size	Type
J-Bat	abandoned	4-1	S-N	3,3rd pole	N Disabled	Gone	None	
EPU-21	Flowing	4-2	W-E	2	Leaning	None	None	
EPU-60	tank, pit	4-3	W-E			Pit bermed	None	
	TA-bullplug	4-4	SW-NE	Removed	Disabled	None	None	
EPU-106	TA-rods	4-5	W-E	3	Disabled	No W berm Gap NE cor.	None	
EPU-31	Oil spill Pumping	4-6 4-7	NW-SE NW-SE	3	In use	No N berm No N berm	3 55gal met	Corr. inhib. Scale inhib.
N. Cent. Battery (S-Bat)	drums & junk old battery new tanks	4-8 4-9 4-10	SSW-NNE ESE-WSW SE-NW	3	In use	No S berm Bermed	55gal drum	Corr. inhib.
Custody xfer stn.	receiving shipping	4-11	E-W		In use	None Sump	None None	
N SWD	pit tanks	4-12 4-13	S-N SE-NW	6	In use	Bermed Bermed Bermed	300gal poly	Corr. inhib.
EPU-1D	SWD							
EPU-78	TA-bullplug	4-14	N-S	Removed	Removed	None	None	
EPU-36	TA-bullplug	4-15	NE-SW	Removed	Removed	None	None	
EPU-69	TA-bullplug	4-16	NE-SW	Removed	Disabled	None	None	
EPU-59	P & A							
EPU-115	P & A							
EPU-102	Flowing	4-17	S-N					
E-Bat	treater tank	4-18 4-19	SSW-NNE SW-NE	3	Disabled	Bermed No E, S berm	None	
EPU-70	Pumping	4-20	SW-NE	3	In use	No W berm	None	
EPU-77	Pumping	4-21	SW-NE	3	In use	No W berm Gap NW	None	

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
4	Valve header	Not observed			Site being reclaimed; rev. spr. 99.
4	N,E,S of well	Not observed			Pad, partial railing, pole, well remain
4	Sludge, pit Frac tank leak W,E wellhead	Not observed Not observed		Flow line - 6 Gear oil jug Pump unit Pump parts	Workover pit with sludge in S part. Frac tank, laid over, has leaked. Pumping unit scavenged; MDU service pole leaning.
3	NW, SE - well	Not observed		Valve box 4x20' pipe Equipment Pump unit	Location is very oily, messy. Pipe & equipment laying around. Location should be reclaimed.
3	Oil on water. Wellhead	Probable Probable		Vacuum line	Site of recent pipeline break. Location should be cleaned up.
3	NW quad-loc.	Location w/o plant life	28 drums	Junk pile Old equip.	Stored outside on pallets-numbered. New treater; oil on water in valve sub Old battery; very messy; being recl. New tanks; good installation. Site probably has oil&SW in GW.
3	A little oil Oily at load pt.	Not observed Little grass		Kitchen chr.	Receiving side seems nearly clean. Shipping side has lots of oil spilled.
3	Oily mess-pit Not observed Not observed	N,E of pit No plants No plants			Pit lined, partially netted, very oily. Probable major area of SW impact N of tanks. Should review spr. 99.
4	E wellhead	Not observed			Pad, partial railing & well remain.
4	NE wellhead	Not observed			Pad, railing, well, monitor well(bkgd.)
3	S wellhead	Not observed		Valve box	Pump parts on ground; need to recl.
3					Found marker; site reclaimed.
3		150' radius well			Site reclaimed, but no life near well.
3	Not observed	Not observed		20' pipe	Lush grass near wellhead.
3	N end berm		5 drums-#6 Sludge	Lots o steel	Messy location; being reclaimed. Tank full of sludge; pump & salvage,
3	Not observed	Outside berm to S, SSE		Serv. pole Trash bbl.	Cattle tracks obscure any oil stain. Major SW problem to S and SSE.
3	Probable	S of berm		Valve box Sucker rods	Cattle tracks obscure any oil stain. Probable SW problem to S of berm.

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size	Type
EPU-46	TA-bullplug equipment reserve pit	4-22 4-23 4-24	E-W SSE-NNW NW-SE	Removed	Removed	None	None	
EPU-10	Pumping	4-25	E-W	3	In use	E, N, NW Gap to NE	2 55gal dr.	Corr.&scale
EPU-23	Flowing TA-valve reserve pit	4-26	SE-NW	Removed	Removed	None	None	
EPU-112	Pumping	4-27	NE-SW	3	In use	No E, W, S	None	
EPU-56	Pumping	5-1	ENE-WSW	3	In use	No E berm Gap to N	150gal poly	Corr. inhib.
EPU-105	Pumping	5-2	W-E	3	In use	Part W berm Gap to NE	None	
Salt prob N of 105								
SWD-5D	pit extra berm pretreat battery	5-3 5-4 5-5	SW-NE SW-NE NW-SE	3	In use	Weak to W	Probable	Corr.&scale
EPU-107	Pumping	5-6	WSW-ENE	3	In use	Bermed Gap to E	None	
I- Bat	SW stress battery tank	5-7 5-8	W-E SE-NW	Removed?	Removed?	No berms No N berm	None	
EPU-19 EPU-4G	TA-bullplug	5-9	SE-NW	Removed	Disabled	N,NW berm	None	
SWD	equipment pit	5-10	SSW-NNE	3	In use	None-bldg Berm-pit	3-55gal met	Corr.&scale Various
EPU-109	P & A							
EPU-92	P & A							

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
3	E of wellhead	E of wellhead		2 tanks 4 treaters	Outside of unit, but has well to P&A and equipment to sell for scrap.
		S of pit	9 drums (6-#1, 3-#2)		Reserve pit breached; stressed soil.
3	Well & E of PU				Workover unit onsite; rods & tubing are in the workover rack.
3	Well, frac tank Along flow line Sludge in pit	Not observed		Frac tank	Appears to be a twinned well. Probable shallow gas well. Reserve pit open with sludge; needs P & A.
3	Wellhead	Unsure		Pipe, fittings Valve box	Flow line recently installed; site under construction; review spr. 99.
3	Wellhead Under water	Not observed		280' tubing	Very muddy; a lot of bermed area is under water.
3	A bit of oil	Not observed			This well is pretty decent.
3					Salt stress from Sec 19 bat crosses road, appears E of road near field.
3	Walls of pit Oil inside berm	E, SE of pit Farmed?		Pipe & fits Lumber Vessel	Lined, netted, & messy pit. Extra berm to protect from pit losses Pre-processing tank is 500' E. Site under construction; needs spr. 99 review. Major SW problem.
2	E of wellhead Lots of gear oil	Not observed			Site needs run-on, run-off control.
3	Not observed Sludge	E, SE off loc. (3rd prior entry)		Equipment Rusted tank Building	Area appears to be amended with straw & manure-in reclamation. Battery & tank abandoned; seem to be targeted for dismantling. Site of major SW problem-rev. again
3	Not observed (but v. muddy)	Wellhead & E		100gal ves. treater tubing	Either twinned, recompleted, or renamed. Obviously abandoned. Should be dismantled, reclaimed.
3	Not observed	Area, E & SE			Building & equipment not bermed. Pit not lined or netted; on gravel hill. Major SW problem; review spr. 99.
3					Site reclaimed.
3					Site reclaimed fall 98.

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANSFORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size	Type
EPU-27	Pumping	5-11	SE-NW	3	In use	S berm	None	
EPU-93	TA-bullplug	5-12	N-S	Removed	Removed	None	None	
EPU-33	P & A							
EPU-84	Pumping	5-13	SW-NE	3	In use	Bermed	None	
EPU-91	TA-rods	5-14	SW-NE	Removed	Disabled panel open	No W berm	None	
EPU-34	TA-bullplug	5-15	W-E	Removed	Disabled	None	None	
EPU-49	P & A							
EPU-R1	P & A							
EPU-53	P & A							
EPU-38	Pumping	misfire	NW-SE	3	In use	None S, W	None?	
M-Bat		6-1	SE-NW					
EPU-90	Pumping?	6-2	E-W	3	In use	No E berm	None	
EPU-98	TA-bullplug	6-3	SSE-NNW	Removed	Removed	Weak to E	None	
WB-1	P & A							
EPU-40	TA-valve	6-4	S-N	Removed	Removed	None	None	
Smith #1	TA-valve	6-5	ENE-WSW	Removed	Removed	None	None	
North Yards	storage	6-5	ENE-WSW	Removed	Removed			
EPU-30	TA-valve	6-6	SW-NE	Removed	Removed	None	None	
EPU-58	TA-rods	6-7	SW-NE	3	Disabled	No N berm Gap to NE	None	

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
2	S-PU & well	Flow line to S Sparse on loc.			Lots of scale on wellhead. Very little plant life along flow line.
2	Not observed	Not observed			Pad, rail, well, & deadmen remain.
2					Reclaimed, no marker. In wheat fld.
1	E wellhead	Not observed			Very muddy access to this location.
1	Wellhead	E, W wellhead		Pump unit	Location abandoned; should be reclaimed.
1	Not observed	Not observed			Site needs abandonment & reclaim.
1					Site reclaimed, no marker, in field.
1					Site reclaimed, no marker, in field.
1				Rods to N	Site is reclaimed; found marker.
1	S, N of well N of berm	N of wellhead N, NW - berm			Well is pretty messy. Probably is a major SW problem.
1					Site is reclaimed, but doesn't have much plant growth today.
1	Lots in berms	Not observed			Well is on timer, or is natural flowing
1	Not observed	N, S wellhead N, S of berm		Elec. serv.	Well is pretty messy. Probably is a minor SW problem.
1					Site is in wheat field; is reclaimed.
1	Not observed	Lush grass		Bridles, rods	Site needs reclaiming.
1	5' rad.-sludge	Stunted- 150'S			Site needs reclaiming.
1				New pipe Used pipe Rusted culv Bldg. fell	Site is junky; abd. treater, vessel, pile of rusted culvert. West add'n. of block building collapsed. Site stores new, used conc. asb. pipe.
1	Not observed	Not observed Lush grass to wellhead		Manifold Bent rods Railing	Well should be P & A'd and the site reclaimed.
1	E, W wellhead	Inside berm E of berm		Fibreglass Metal Elec. panel	Site is abandoned, but is probably impacted by SW loss. Should be reviewed in spring 99.

WELL NO.	WELL STATUS	PHOTO NO.	DIRECTION	TRANS-FORMERS	SERVICE POLE	CONTAIN. DIKE	CHEMICALS Size	Type
L-Bat	battery tank	6-8	N-S	Removed	Disabled	Removed	None	
EPU-73	Pumping	6-9	WNW-ESE	3	In use	None E, W Gap to S	None	
EPU-94	TA-rods	6-10	ENE-WSW	Removed	Disabled	None	None	
EPU-65U	P & A							
EPU-65	TA-bullplug	6-11	WSW-ENE	Removed	Removed	No W berm Gap N berm	None	
EPU-48	TA-valve	6-12	WSW-ENE	Removed	Removed	None	None	
EPU-37	TA-bullplug	6-13	NW-SE	Removed	Removed	None	None	
P-Bat	abandoned							
EPU-75	P & A							
EPU-54	TA-rods			Removed	Disabled	No W berm	None	
EPU-71	TA-bullplug	6-14	S-N	Removed	Removed			
EPU-111	Pumping	6-15	S-N	3	In use	Bermed Gap to SE	None	
EPU-95	TA-rods			3	In use?	None to SE	None	
Repairs								
Metal building							500gal poly	Corr. inhib.
Workover pit								
McGowan battery tank						W,S berm W,S berm		

MAP NO.	CRUDE SPILLS	STRESSED VEGE.	WASTE DRUMS	JUNK	COMMENTS
2	Around treater Inside berm Around tank? S along flow line				Site is partly dismantled. Tank? is gone, but treater remains. Review spring 99 for SW damage.
2	S of wellhead	Not observed			Needs berming.
2	Wellhead	Service pole E,W wellhead		Pump unit Valve box	Site is not tidy. Signs of SW spill. Needs to be abandoned, reclaim.
2					Found pit & pad, no marker.
2	N,E,SE - well	Wellhead SSE of berm		Cable	Site shows signs of salt water spill. Reclaim & review, spring 99.
2	E,W,SW - well	Wellhead			Abandon & reclaim.
2	N&W - well	Not apparent			Abandon & reclaim.
2					Lots of stressed plants along piping. May have caused major erosion.
2					Site reclaimed; in pasture.
2	Wellhead	Location		Belts,guard	Abandon & reclaim.
2					Pad & railing remain; site reclaimed.
2	Well, 15' radius			Rod Couplers	Fairly recent well; lots of equipment. 1/2 mile to W. May want to look W.
2	E,W wellhead Frac tank valve	Not observed		Pump parts Frac tank	Recently TA'd. If production not restored, abandon site & reclaim.
2					Recent break repaired 1/3 of way from 95 to 111.
2					East of EPU-95. South of EPU-95; no liner or net, not secured; gravelly, has water.
2	KO & 40' to W Oil on water-S Pipe connects				Knockout area is messy. Berms are in place on low sides. Reinspect site in spring 99.

APPENDIX C

Photograph Log of Inspected Production Equipment and Locations

EPU-37

6-13
NW-SE

Long Creek East
(2)



EPU-71

6-14
S-N

Long Creek East
(2)



EPU-111

6-15
S-N

Long Creek East
(2)





EPU-94

6-10
ENE-WSW

Long Creek East
(2)



EPU-65

6-11
WNW-ESE

Long Creek East
(2)



EPU-48

6-12
WSW-ENE

Long Creek East
(2)

EPU-58

6-7
SW-NE

Geddart Lake
(1)



L-Battery

6-8
N-S

Long Creek East
(2)



EPU-73

6-9
WNW-ESE

Long Creek East
(2)





EPU-40

6-4
S-N

Geddart Lake
(1)



Smith 1
(N. Yards-Bkgd.)

6-5
ENE-WSW

Geddart Lake
(1)



EPU-30

6-6
SW-NE

Geddart Lake
(1)



EPU-84

5-13
SW-NE

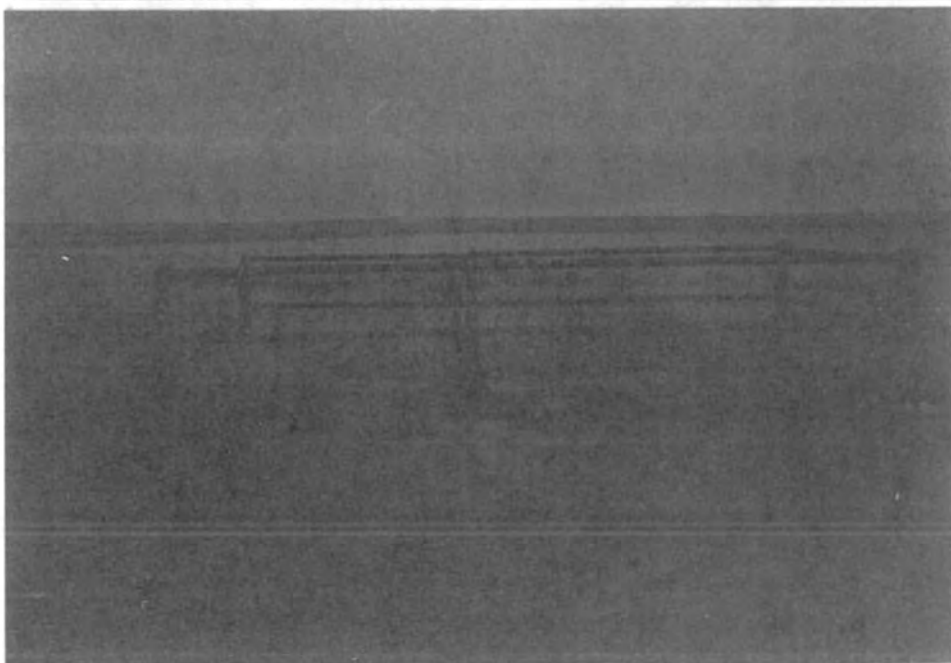
Geddart Lake
(1)



EPU-91

5-14
SW-NE

Geddart Lake
(1)



EPU-34

5-15
W-E

Geddart Lake
(1)

M-Battery

6-1
SE-NW

Geddart Lake
(1)



EPU-90

6-2
E-W

Geddart Lake
(1)



EPU-98

6-3
SSE-NNW

Geddart Lake
(1)





**I-Battery
Amended Soil**

5-7
W-E

Badger Creek
(3)



**I-BATTERY
Battery**

5-8
SE-NW

Badger Creek
(3)



**EPU-19
EPU-4G**

5-9
SE-NW

Badger Creek
(3)

**Salt Water Disp.5
Equipment & Pit**

5-10
SSW-NNE

Badger Creek
(3)



EPU-27

5-11
SE-NW

Long Creek East
(2)



EPU-93

5-12
N-S

Long Creek East
(2)





EPU-56

**5-1
ENE-WSW**

**Badger Creek
(3)**



EPU-105

**5-2
W-E**

**Badger Creek
(3)**



**Saltwater Disp#5
Pit & Extra Berm**

**5-3
SW-NE**

**Badger Creek
(3)**

**Saltwater Disp#5
Pretreat**

5-4
SW-NE

Badger Creek
(3)



**Saltwater Disp#5
Battery**

5-5
NW-SE

Badger Creek
(3)



EPU-107

5-6
WSW-ENE

Long Cr. East
(2)

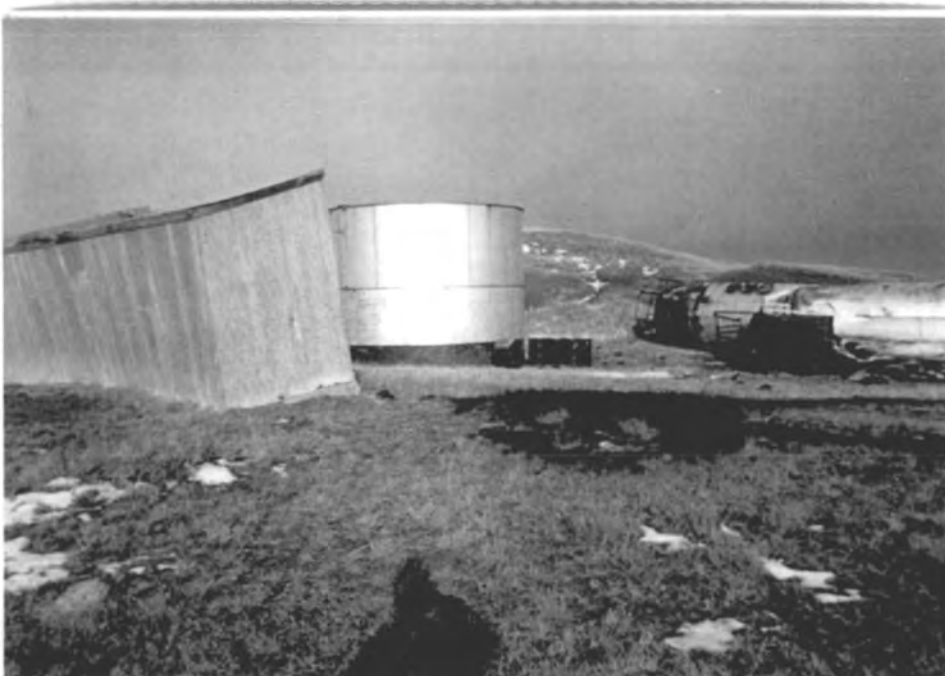




**EPU-46
Well**

4-22
E-W

Badger Creek
(3)



**EPU-46
Location**

4-23
SSE-NNW

Badger Creek
(3)



**EPU-46
Reserve Pit**

4-24
NW-SE

Badger Creek
(3)

EPU-10

4-25
E-W

Badger Creek
(3)



EPU-23

4-26
SE-NW

Badger Creek
(3)



EPU-112

4-27
NE-SW

Badger Creek
(3)





**EPU-46
Well**

4-22
E-W

Badger Creek
(3)



**EPU-46
Location**

4-23
SSE-NNW

Badger Creek
(3)



**EPU-46
Reserve Pit**

4-24
NW-SE

Badger Creek
(3)



EPU-69

4-16
NE-SW

Badger Creek
(3)



EPU-102

4-17
S-N

Badger Creek
(3)



E-Battery
Treater

4-18
SSW-NNE

Badger Creek
(3)

**E-Battery
Tank**

4-19
SW-NE

Badger Creek
(3)



EPU-70

4-20
SW-NE

Badger Creek
(3)



EPU-77

4-21
SW-NE

Badger Creek
(3)





**N Central Bat.
New Tanks**

4-10
SE-NW

Badger Creek
(3)



**Crude Custody
Transfer Station**

4-11
E-W

Badger Creek
(3)



**NC SW Disp.
Pit**

4-12
S-N

Badger Creek
(3)

NC SW Disp.
Tanks & EPU-1D

4-13
SE-NW

Badger Creek
(3)



EPU-78

4-14
N-S

Poplar
(4)



EPU-36

4-15
NE-SW

Poplar
(4)





**EPU-60
Well**

4-4
SW-NE

Poplar
(4)



EPU-106

4-5
W-E

Badger Creek
(3)



**EPU-31
Oil Spill**

4-6
NW-SE

Badger Creek
(3)

EPU-31
Well

4-7
NW-SE

Badger Creek
(3)



N Central Bat.
Drums & Junk

4-8
SSW-NNE

Badger Creek
(3)



N Central Bat.
Old Battery

4-9
ESE-WNW

Badger Creek
(3)





EPU-97

3-25
SE-NW

Poplar
(4)



EPU-96

3-26
WSW-ENE

Poplar
(4)



EPU-110

3-27
NE-SW

Poplar
(4)

**J-Battery
West of EPU-110**

4-1
S-N

Poplar
(4)



EPU-21

4-2
W-E

Poplar
(4)



**EPU-60
Frac tank & pit**

4-3
W-E

Poplar
(4)





**Salt Water - 6
Salt Water Spill**

3-19
SE-NW

Poplar
(4)



EPU-81

3-20
W-E

Poplar
(4)



EPU-62

3-21
E-W

Geddart Lake
(1)

EPU-103

3-22
E-W

Poplar
(4)



EPU-47

3-23
E-W

Poplar
(4)



EPU-79

3-24
NE-SW

Poplar
(4)





EPU-114

3-13
NW-SE

Poplar
(4)



EPU-42

3-14
SW-NE

Poplar
(4)



**N-BATTERY
Tanks & Transfer**

3-15
ESE-WNW

Poplar
(4)

**N-BATTERY
Treater**

3-16
SE-NW

Poplar
(4)



**Salt Water - 6
Treater**

3-17
NE-SW

Poplar
(4)



**Salt Water - 6
Tanks**

3-18
E-W

Poplar
(4)





EPU-43

3-7
E-W

Poplar
(4)



EPU-66

3-8
SE-NW

Poplar
(4)



Q-BATTERY
Treater

3-9
NW-SE

Poplar
(4)

EPU-89

3-10
W-E

Poplar
(4)



EPU-83

3-11
SE-NW

Poplar
(4)



EPU-57

3-12
SW-NE

Poplar
(4)





EPU-18

3-1
SE-NW

Poplar
(4)



EPU-1

3-2
SW-NE

Poplar
(4)



EPU-16

3-3
NE-SW

Poplar
(4)

EPU-4

3-4
SE-NW

Poplar
(4)



EPU-3

3-5
N-S

Poplar
(4)



EPU-88

3-6
ENE-WSW

Poplar
(4)





EPU-45

2-22
SW-NE

Badger Creek
(3)



EPU-5

2-23
SE-NW

Poplar
(4)



**C-Battery
Treater**

2-24
SE-NW

Poplar
(4)

**C-Battery
Pump & tanks**

2-25
SE-NW

Poplar
(4)



**Flow line repairs
Near C-Battery**

2-26
ESE-WNW

Poplar
(4)



EPU-85

2-27
E-W

Poplar
(4)





EPU-39

2-16
SE-NW

Poplar
(4)



EPU-80D
Salt water pit

2-17
N-S

Badger Creek
(3)



EPU-80D
Wood Tank

2-18
ESE-WNW

Badger Creek
(3)

EPU-80D
Stressed Veg.

2-19
ESE-WNW

Badger Creek
(3)



EPU-80D
Salt Water Disp.

2-20
SW-NE

Badger Creek
(3)



EPU-41

2-21
WSW-ESE

Badger Creek
(3)





Huber 6
Salt Water Disp.

2-10
W-E

Poplar
(4)



Huber 3

2-11
N-S

Poplar
(4)



Huber 1

2-12
SE-NW

Poplar
(4)

EPU-14

2-13
N-S

Poplar
(4)



F-Battery
Backhoe Pit

2-14
SE-NW

Poplar
(4)



F-Battery
The battery

2-15
S-N

Poplar
(4)





**Huber Battery
Treaters**

2-4
SW-NE

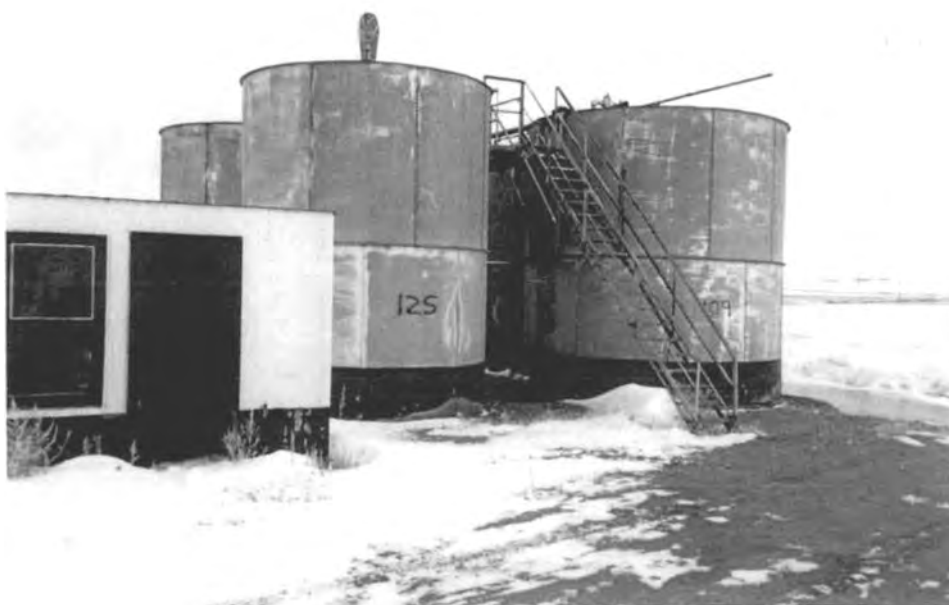
Poplar
(4)



**Huber Battery
Saltwater Spill**

2-5
SW-NE

Poplar
(4)



**Huber Battery
Transfer & Tanks**

2-6
SSW-NNE

Poplar
(4)

Huber 4

2-7
N-S

Poplar
(4)



Huber 4A

2-8
NW-SE

Poplar
(4)



Huber 2

2-9
N-S

Poplar
(4)





EPU-12

1-25
SE-NW

Poplar
(4)



**South Central
Saltwater Disp.**

1-26
SE-NW

Poplar
(4)



**South Central
Saltwater Disp.**

1-27
E-W

Poplar
(4)

Pumpers' Shed

2-1
SE-NW

Poplar
(4)



Huber 5

2-2
ENE-WSW

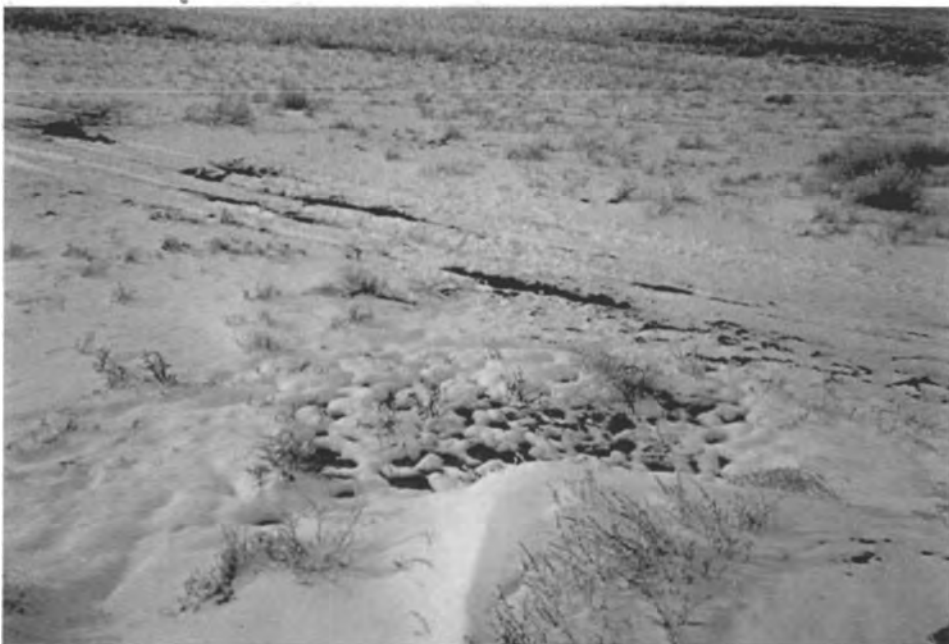
Poplar
(4)



**Huber Battery
Crude Spill**

2-3
NE-SW

Poplar
(4)





EPU-7

1-19
SE-NW

Poplar
(4)



EPU-6

1-20
N-S

Poplar
(4)



South Central
Battery

1-21
NE-SW

Poplar
(4)

**South Central
Transfer Stn.**

1-22
N-S

Poplar
(4)



**South Central
Tanks**

1-23
WNW-ESE

Poplar
(4)



**South Central
Pit**

1-24
ENE-WSW

Poplar
(4)





**K-Battery
Aband'ned treater**

1-13
N-S

Poplar
(4).



**K-Battery
New flow line**

1-14
WNW-ESE

Poplar
(4)



EPU-100

1-15
NE-SW

Poplar
(4)

EPU-68

1-16
E-W

Poplar
(4)



EPU-24

1-17
NW-SE

Poplar
(4)



EPU-15

1-18
E-W

Poplar
(4)





**H-Battery
Abandoned tanks**

1-7
SE-NW

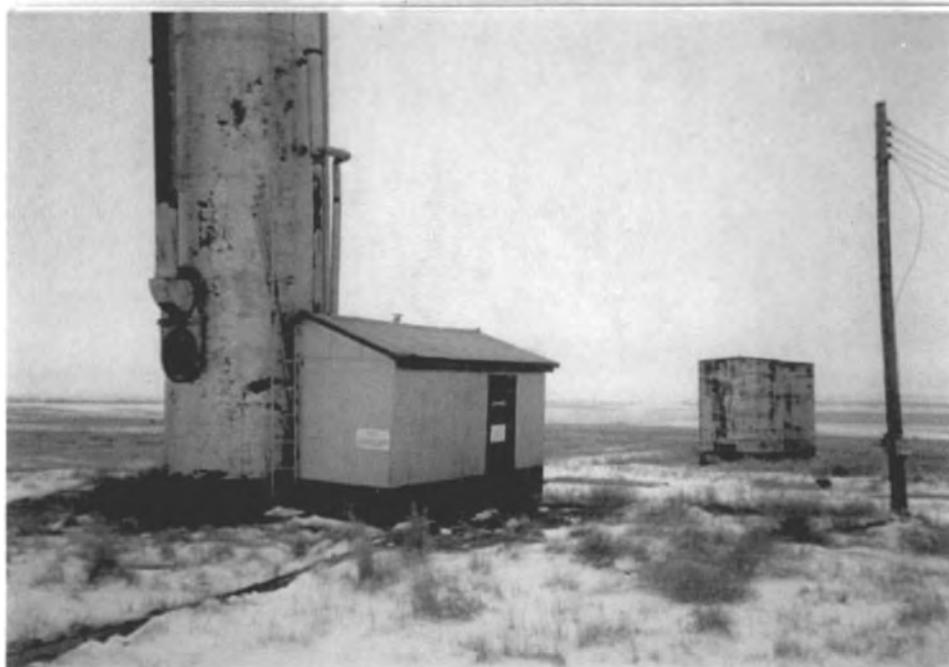
Poplar
(4)



**H-Battery
Abandoned well**

1-8
S-N

Poplar
(4)



**H-Battery
Aband'ned treater**

1-9
NE-SW

Poplar
(4)

EPU-32

1-10
SSW-NNE

Poplar
(4)



EPU-101

1-11
NE-SW

Poplar
(4)



EPU-9

1-12
ENE-WSW

Poplar
(4)

